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Pattern Division Multiple Access: A New Multiple Access Technology for 5G

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ABSTRACT-*The anticipated 1000-fold increase in mobile data traffic over the next decade and the explosion of new services and applications pose great challenges for the current orthogonal multiple access (OMA)-based 4G systems. A promising solution to address these challenges is to shift from the currently predominant OMA to non-orthogonal multiple access (NOMA). This article first introduces the principle of the complexity-constrained capacity-achieving NOMA design. Then a non-orthogonal pattern division multiple access (PDMA) scheme is proposed to meet the exponentially growing demand of mobile users for computing and information application services. The key feature of the PDMA scheme is a joint design of transmitter and receiver, which allows low-complexity successive interference cancellation (SIC)-based multi-user detection with substantially improved performance over conventional OMA schemes. More specifically, the patterns of multiple users are judiciously designed so that the data symbols of different users are of appropriate diversity disparity at the symbol level and power disparity at the resource element level. The appropriate disparity in diversity and power can be effectively exploited by the low-complexity SICbased detector to realize the near-perfect cancellation of multi-user interference. Moreover, the PDMA system parameters can be flexibly adjusted to provide different levels of overload, rendering it suitable to meet the diverse traffic requirements in future 5G systems. Link-level simulations illustrate that PDMA is capable of accommodating a 300 percent overload, while it still enjoys transmission reliability close to conventional OMA schemes. The results demonstrated in this article indicate that PDMA can be a promising multiple access technology with low signaling overhead, low latency, and massive connectivity support for 5G.*

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I. INRRODUCTION

The unprecedented increase of mobile data traffic brought about by the wide proliferation of smartphones and tablet computers is driving the wireless communications industry to undergo an unprecedented paradigm shift [1]. In addition, the advent of the Internet of Things (IoT) will enable new ways to monitor, assist, secure, and control smart homes, smart factories, and so on, which opens up a broad range of diverse applications ranging from mission-critical services to massive deployment of autonomous devices. These new services may require the fifth generation (5G) networks to support massive connectivity of users and/or devices to meet the demand for low latency, low-cost devices, and diverse service types. Fast and efficient multiple access is the key technology to handle the massive number of sporadic traffic-generating devices, such as the devices which are inactive most of the time but regularly access the network for minor updates without human interaction. The current wireless communication systems have predominantly adopted orthogonal multiple access (OMA) schemes, where users are allocated orthogonal physical resources in the time, frequency, or space domain. Existing OMA schemes efficiently eliminate multi-user interference and thus allow relatively simple transceiver implementations. However, it is shown that OMA schemes achieve strictly lower capacity than non-orthogonal multiple access (NOMA) schemes in the downlink broadcast channel (BC) [2]. Such inefficiency of OMA schemes is even exacerbated in the uplink scenario [3]. Dimensioning the channel access based on existing OMA paradigms may lead to a severe waste of physical resources or even fail to work in massive connectivity scenarios, such as the IoT applications. To support the daunting task of massive sporadic connections, the wireless research community is exploring different technical approaches, such as novel cellular network architectures, massive multiple-input multiple-output (MIMO) techniques, spectrum utilizations at untapped millimeter-wave frequency bands, new waveform designs, and novel multiple access technologies. Among these potential solutions, the NOMA approach is especially suitable for meeting the requirement of massive connectivity, and it is also efficient in reducing transmission latency and improving energy efficiency [4–8]. It has been proven that NOMA is optimal in achieving the entire capacity region of the BC [2] and exhibits higher spectral and energy efficiency than OMA for delay-sensitive applications in the multiple access channel (MAC) [3]. However, the theoretically predicted gains of NOMA over OMA rely on proper multi-user signal separation at the receiver. To reap the full benefits of NOMA, the maximum a posteriori probability (MAP) multi-user detection (MUD) technique can be utilized to achieve the desired performance. The computational complexity of the MAP MUD scales exponentially with the number of users and imposes a formidable challenge to practical hardware implementations. As an alternative to the optimal MAP detector, the low-complexity successive interference cancellation (SIC)-based detector with single-user decoding is able to achieve the Shannon capacity region boundaries in both the BC and MAC scenarios [9, 10]. Nonetheless, one main disadvantage of SIC-based detectors is that errors occurring in detection of transmitted symbols will propagate further into subsequent symbols due to interference subtraction. Such error propagation may severely degrade the system performance, especially when the number of users is large. In this article, we first introduce the complexity-constrained capacity-achieving NOMA design principle, which was not addressed in [7, 8]. Then we propose a non-orthogonal pattern division multiple access (PDMA) scheme based on a joint design of the transmitter and an SIC-based detector at the receiver for the uncorrelated and correlated channel scenarios. The latter is an extension of [7, 8]. The patterns of different users are judiciously designed to exhibit appropriate diversity disparity at the symbol level and power disparity at the physical resource element level. Such diversity disparity and power disparity among users can be effectively exploited by the SIC-based detector to achieve near-perfect cancellation of multi-user interference. Furthermore, the PDMA system parameters can be flexibly adjusted to support a wide range of overload to accommodate diverse applications. The analysis based on the constellation-constrained (CC) capacity shows that the PDMA scheme outperforms conventional OMA schemes with affordable computational complexity. In addition, an

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iterative detection and decoding (IDD)-based receiver [11] structure is elaborated to improve the performance of the PDMA scheme. Link-level simulations show that the PDMA scheme is able to support up to 300 percent overload and achieves significant performance gains over conventional OMA schemes. The superior performance on massive connectivity support is also verified by system-level simulations.

II. System Model

Basics of the SIC-Based Detector

The SIC-based detector [2] iteratively decodes symbols by subtracting the detected symbols of strong users first to facilitate the following detection of weak users. The decoded data of the early detected symbol is re-encoded, and by using accurate channel knowledge, it can be reconstructed to closely resemble the real transmitted signal. However, the error propagation resulting from low diversity of early SIC detection stages may severely degrade the system performance. It is generally accepted that, for a system equipped with an SIC-based detector, the performance is highly dependent on the first-step detection accuracy. The low-complexity belief propagation (BP) algorithm and its variant SIC-BP [12] are shown to be able to achieve a close approximation of the MAP MUD. The SIC-BP algorithm solves inference problems, exactly or approximately, via probabilistic graphical models [12]. The SIC-BP algorithm obtains a posteriori estimates of the system unknowns by iteratively passing locally calculated conditional probabilities between variable and function nodes [12]. Similar to SIC-based detectors, the performance of the SIC-BP algorithm is also determined by the initial inference accuracy of the transmitted symbols involved with the iterative detection process. This observation suggests that enhancing the first-step inference accuracy is of paramount importance for improving the overall performance of non-orthogonal systems employing an SIC-based detector, such as the BP algorithm. We first introduce some notations for the PDMA scheme, where K users can non-orthogonally share $N(N < K)$ orthogonal radio resource elements, a chip for the code-division multiple access (CDMA) system, and a subcarrier for the orthogonal frequency-division multiple access (OFDMA) system. The overload factor, which is the ratio of the number of users to the total number of utilized physical resource elements, is defined as a = K/N. The pattern matrix of the PDMA is defined as S = [s1, s2, …,sK], where sk = [s1k, s2k, …sNk]T denotes the pattern for user k. The set of positions of non-zero elements in the nth row of the pattern matrix S denotes the set of users that contribute their data at the physical resource element. In addition, the pattern matrix S consists of groups of user patterns with the same number of non-zero entries. The design philosophy of the PDMA scheme is that user signals are judiciously allocated in a specific physical resource space (frequency, code, or spatial domain) at the transmitter, which can be effectively exploited to enhance the performance of SIC-based detectors at the receiver. More specifically, the data of different users should exhibit appropriate diversity disparity at the symbol level and power disparity at the physical resource element level. Such disparities are expected to introduce a convergence-amenable characteristic that can be fully exploited by the SIC-based detector in eliminating multi-user interference as well as retrieving transmit diversity at the receiver. Inspired by the properties of the SIC-based detector discussed earlier, we present a non-orthogonal PDMA scheme where the corresponding pattern matrix has the following three features:

1. The number of groups having different numbers of non-zero elements in the pattern matrix is maximized.
2. The interference among the user patterns in the same type group is minimized.
3. The size of each group is maximized to the degree allowable by the computational complexity constraints (further detailed earlier). The maximum number of supported users K for the PDMA scheme with N orthogonal physical resource elements is given by K = C1 N + C2 N + … + CN N = 2N – 1, where Cn N denotes the number of all n-combinations of a set N. Depending on whether the user's data is sent consecutively or in a distributed manner, we propose a distributed-mapping-based PDMA and a localized-mapping-based PDMA, respectively, as below

III. LITERATURE SURVAY

Radio access technologies for cellular mobile communications are typically characterized by multiple access schemes, e.g., frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), and OFDMA. In the 3.9 and 4th generation (4G) mobile communication systems such as Long-Term Evolution (LTE) [1] and LTE-Advanced [2, 3], standardized by the 3rd Generation Partnership Project (3GPP), orthogonal multiple access based on OFDMA or single carrier (SC)- FDMA is adopted. Orthogonal multiple access was a reasonable choice for achieving good system-level throughput performance in packet-domain services with simple single-user detection. However, considering future radio access (FRA) in the 2020s, further enhancement to achieve significant gains in capacity and system throughput performance is a high priority requirement in view of the recent exponential increase in the volume of mobile traffic, e.g., beyond a 500 fold increase in the next decade [4], and the need for enhanced delay-sensitive high-volume services such as video streaming and cloud computing. Thus, the 3GPP recently has initiated discussions on further evolution of LTE towards the future, i.e., Release 12 and onwards. In order to continue to ensure the sustainability of 3GPP radio access technologies over the coming decade, new solutions must be identified and provided that can respond to future challenges [4, 5]. Also, recent trends in research activity for the next generation of mobile and wireless communication systems for 2020 and beyond have emerged such as the Mobile and wireless communications Enablers for the 2020 Information Society (METIS) project [6]. To accommodate such demands, a combination of multiple approaches, i.e., technologies for spectrum efficiency enhancement, spectrum extension with efficient use of higher frequency bands, and network densification deploying small cells would be required. In this sense, innovative radio access technologies to enhance significantly the spectrum efficiency and the small-cell enhancement now on-going in the 3GPP are very important [7]. Although it may be very challenging, our target for FRA toward the 2020s is to achieve a further 3-fold enhancement in the spectrum efficiency compared to the LTE baseline. Since LTE has already achieved a 3-4 fold enhancement in the spectrum efficiency compared to 3G HighSpeed Packet Access (HSPA), our target gain would be more than 10 fold compared to the 3G HSPA. Thus, for instance, the gain in the total capacity such as beyond 500 fold can be achieved if other ways, i.e., spectrum extension using higher frequency bands and network densification achieve a capacity gain of 50 fold.

Multiple access schemes for 3G (WCDMA/HSPA), 3.9/4G (LTE/LTE-Advanced), and our expected FRA for the 2020s. In 3G, non-orthogonal user multiplexing based on direct sequence (DS)-CDMA is used. The receiver uses simple single-user detection such as the Rake receiver. Fast transmission power control (TPC) is adopted to address the well-known near-far problem in cellular deployments due to its non-orthogonal property. In 3.9/4G, orthogonal user multiplexing based on OFDMA or SCFDMA is adopted to achieve higher throughput performance in packet-domain services. Its signal waveform such as orthogonal frequency division multiplexing (OFDM), including discrete Fourier transformation (DFT)-spread OFDM [1], provides important benefits, i.e., robustness against multipath interference and good affinity to MIMO technologies, that dramatically increase the achievable data rate. Furthermore, fast TPC becomes non-essential because there is no near-far problem in orthogonal user multiplexing.

IV. PROPOSED SYSTEM

BP-Based MUD: In this section, we describe the BP-based algorithm [12], which can effectively exploit the SIC-amenable structure of the PDMA scheme to obtain near-optimal MUD. BP is an efficient iterative message passing algorithm for computing the marginal a posteriori distributions, which is designed on the factor graph (FG) of the underlying Bayesian inference networks [12]. Figure 1 illustrates the FG of the PDMA scheme with pattern matrix Sdm (3×7) , where the FG is a bipartite graph containing two types of nodes: variable nodes (VNs) and function nodes (FNs). In Fig. 1, each VN xk (representing a user) is denoted by a circle, while each FN yn (representing a physical resource element) is illustrated by a square, and dn f denotes the number of connected VNs for FN yn, e.g., dn f = 4, ∀n of Sdm (3×7) . The messages are updated by iteratively exchanging them between FNs and VNs along the respective edges (representing the non-zero element of the PDMA matrix). When the FG contains no loops, the BP algorithm can be used to perform exact inference for each symbol after a sufficient number of iterations [12]. Operating on the FG of the PDMA scheme, the BP algorithm iteratively approximates the global MAP detection by factorizing it into a product of simpler local observations. When the FG contains cycles, it may lead the BP algorithm to converge to imprecise conditional distributions or, more critically, to diverge. PDMA consists of groups of users with different diversity orders at the symbol level and different power levels at the resource element level. The structural irregularity of the PDMA pattern matrix is beneficial for initiating the convergence of the iterative detection, especially for the most difficult equi-powered case denotes the maximum row weight of S and |X| represents the size of the modulation order, which is considerably lower than O(│X│K) of the optimal MAP MUD. Turbo BP for MUD Enhancement: We can further enhance the performance of the BP-based MUD by combing the BP detector with the channel decoder to form an outer-loop turbo BP receiver structure. Figure 2 illustrates that two outer-loop iterations (labeled Outer-it) can enhance the link-level performance for a PDMA system with 300 percent overload by about 2.1 dB at block error rate (BLER) of 10–2 over the BP-based MUD without outer-loop iteration (i.e., Outer-it = 0).

PDMA for Massive Connectivity Applications: A key performance indicator (KPI) for 5G is the ability to support massive connectivity with a large number of devices such as smartphones, tablet computers, and IoT devices. In this section, we first provide the link-level simulation of a PDMA system with different overload factors. We then carry out the system-level simulation to illustrate its advantages over conventional OMA schemes for massive connectivity applications.

Support of Flexible and Large Overload:

For a PDMA system, the maximum overload factor increases as the length of pattern N increases. For the number of orthogonal radio resource elements N = 2, 3, and 4, the maximum overload factor can be 150, 233, and 375 percent, respectively. Therefore, by varying N, we can accommodate a flexible overload for versatile applications. We evaluated the performance of the PDMA via a link-level simulation. The ITU Urban Macro (UMa) channel with a 2 GHz carrier frequency was adopted. The maximum Doppler frequency, fd, was set to 5.55 Hz, which corresponds to 3 km/h at the carrier frequency of 2 GHz. A perfect channel state information is assumed. In all scenarios, QPSK was employed, and

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the maximum throughput of each user was assumed to be the same. Figure 4 illustrates the curves of average BLER of all users of PDMA with the overload factors 150, 233, and 300 percent (the first 12 columns of Sdm (4×15)), respectively. The BLER results of the OMA-based 4G system were also provided as a baseline. It is shown from Fig. 4 that the BLER performance of the PDMA degrades as the overload factor increases in the intermediate SNR region. As the SNR increases, the BLER performance of the PDMA approaches that of the 150 percent case, indicating a near-perfect interference cancellation for PDMA even with a high overload. The maximum network throughput can be increased by 200 percent (this is not shown due to space constraints). The better performance of PDMA over OFDMA is explained as follows: The PDMA users exhibit either better diversity order (for those with df>1) or better frequency diversity than that of OFDMA.

Support of Massive Connectivity in Contention-Based Scenarios: In this subsection, we present a system-level simulation of the potential gains of PDMA over the OFDMA scheme (currently used by 4G) in contention-based scenarios. We consider an application scenario for small packet transmission with tight latency constraints. We employ a 19-hexagonal macrocell model with 3 sectors per cell. The cell radius of each macrocell is set to be 500 m. The locations of the users are randomly assigned with uniform distribution. The system bandwidth is set to 10 MHz, and the transmission power of the macrocell is 46 dBm. The antenna gains at the macrocell and user equipment (UE) are 17 dBi and 0 dBi, respectively. The contention region is set to be 6 resource block (RB) pairs. Uplink traffic for each user follows Poisson distribution with a mean packet inter-arrival time of 120 ms per user. The turbo BP receiver is employed for PDMA, while a linear MMSE receiver is employed for OFDMA. The system performance is evaluated in terms of outage probability, where the system outage is defined as the user's packet drop rate being larger than 1 or 5 percent. Figure 6 illustrates that PDMA can support 116 users for system outage of 5 percent, while conventional OFDMA can only accommodate 46 users; that is, about 1.5 times more users can be supported by PDMA. For a system outage of 1 percent, PDMA is able to achieve a more prominent performance gain; that is, about 2.2 times more users can be accommodated by PDMA. Thus, PDMA demonstrates an obvious advantage over OFDMA in terms of supported number of users while achieving the same system outage performance.

V. SIMULATION RESULTS

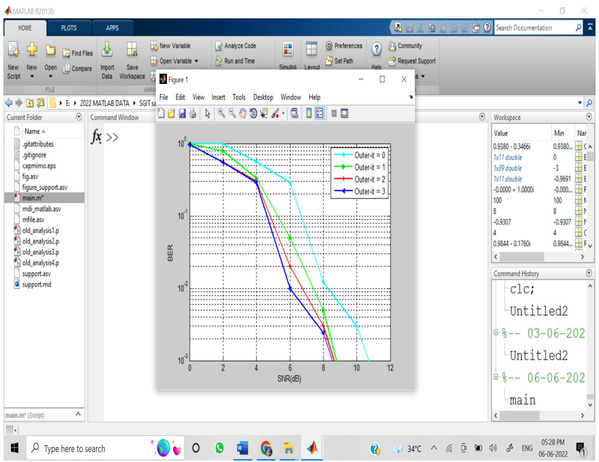

FIGURE 1. Turbo BP receiver structure for the PDMA and its performance.

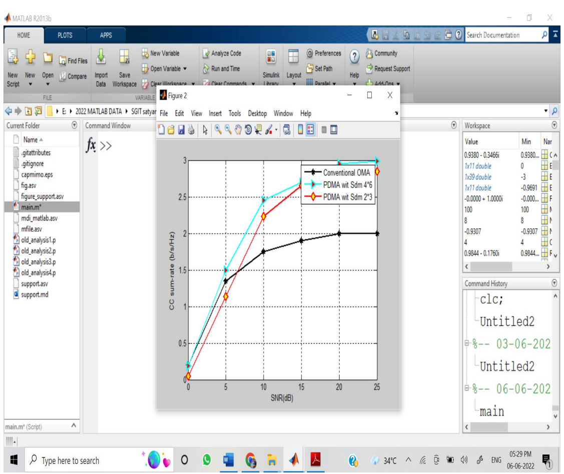

FIGURE 2. Comparison of CC sum-rate of the PDMA scheme and the OMA scheme.

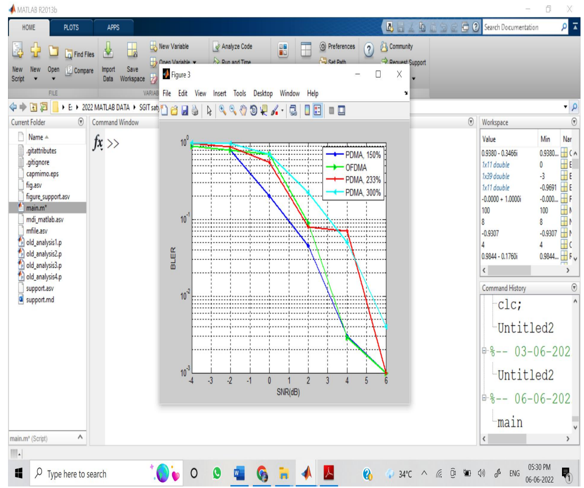

FIGURE 3. BLER performance of the PDMA with different overload factors in the uplink.

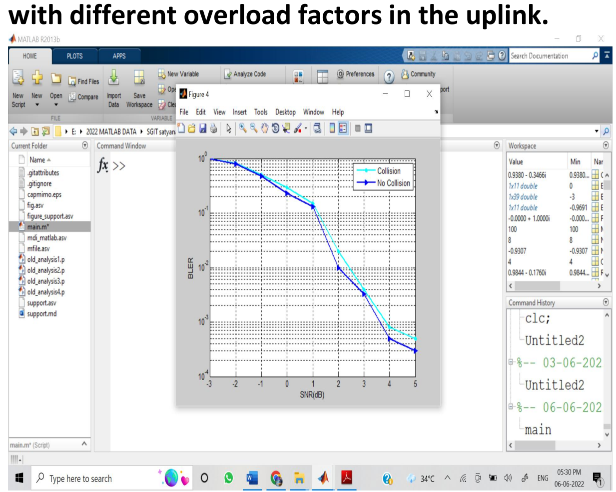

FIGURE 4. Performance of user collision.

VI. CONCLUSION

we first introduce the complexity-constrained capacity-achieving NOMA design principle. Then a new NOMA scheme named PDMA was devised. The PDMA scheme is based on a joint transmitter and receiver design that facilitates low-complexity SIC-based MUD with substantially improved performance over conventional OMA schemes. The PDMA scheme is flexibly designed to accommodate various over loads and is thus suitable for diverse applications. Furthermore, PDMA exhibits robust collision tolerance and is amenable to grant-free scenarios, which is essential for IoT applications. Numerical results from link-level and system-level simulations illustrate that PDMA is a promising candidate technique for 5G multiple access due to it being able to triple the overall system throughput while keeping a link performance close to orthogonal transmissions.

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