A NOVEL JOINT INDEX MODULATION AND PHYSICAL LAYER NETWORK CODING MECHANISM FOR BEYOND 5G

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ABSTRACT

In beyond 5G communications, besides energy efficiency (EE) and spectral efficiency (SE), latency and reliability are among the main metrics that extreme ultra-reliable low-latency communications (URLLC) applications must fulfill. Although new techniques are sought after to meet the crunching requirements of URLLC, combining existing physical-layer techniques have become a compelling, attractive, and cost saving approach to achieving the same goal. In this article, we describe a novel mechanism combining physical layer network coding (PNC) and index modulation (IM) to achieve a balance between SE and EE for URLLC applications beyond 5G. PNC has the potential to increase SE because it leverages on interference from many transmissions occurring at the same time. Although fewer resources are required for IM, the capacity gain is the same as if all transmission resources are used, and as a result, both EE and SE can increase simultaneously. Our simulation results show the feasibility of combining these two key physical-layer techniques, affirming the complementary role this approach will play in meeting the performance KPIs of URLLC beyond 5G.

INTRODUCTION

The wireless communication era beyond 5G will be augmented by novel enabling technologies. However, it is expected that a mix of existing technologies will be in place to satisfy the crunching requirements beyond 5G. The wireless medium is expected to continue to be interference-limited. Beyond 5G, there will be a plethora of transmission technologies coexisting and efficiently using the existing sub-6 GHz spectrum and new spectrum such as millimeter-wave (mmWave) and terahertz (THz) bands. Physical layer network coding (PNC) is a key physical-layer technique that overcomes interference by applying network coding (NC) to received radio signals, which constitutes a superposition of a multitude of transmitted signals.

Due to the challenges in meeting the stringent requirements of ultra-reliable low-latency communications (URLLC), this 5G use case is expected to be one of the main use cases for beyond 5G [1] and even expected to evolve. In beyond 5G communications, URLLC applications are expected to meet extremely low latency and high reliability requirements. Designing systems that meet these requirements is very challenging. Much like EE and SE, latency and reliability are two metrics that are conflicting, as improving one degrades the other. Therefore, physical-layer techniques that strike a good balance between EE and SE are some of the most sought after beyond 5G technologies. Index modulation (IM) is a promising physical-layer technique that is capable of meeting the trade-off between EE and SE. IM allows few resources to be used during transmission, reducing the EE butt guaranteeing the achievable SE. PNC has extensively been studied in the literature [2]. While IM requires fewer resources to achieve the same capacity as techniques that use all resources, PNC, on the other hand, requires that all the available resources be used at the same time by all nodes that transmit. There is no orthogonality; therefore, the number of time slots required to achieve end-to-end communications is reduced by 2. In URLLC applications, this will complement meeting the latency requirement. A combination of IM and PNC is expected to boost capacity while meeting the SE, EE, and latency requirements of URLLC.

The rest of the article is organized as follows. We describe the concept of PNC to some degree of detail. Then we introduce the concept of IM, focusing on a variant of it called spatial modulation (SM). Next, our novel mechanism combining PNC and IM is presented, complementing the article with a simulation result analysis.

PHYSICAL-LAYER NETWORK CODING

PNC is no longer a new concept considering the numerous works in the literature involving this technique and its propensity for being utilized in the future generation of wireless technologies [2–5]. It is the adoption of the network layer NC at the physical layer of wireless communication systems.

NC is a data dissemination paradigm in a distributed multihop relay network, where, instead of simply relaying the received packets, each node takes several packets and combines them, and the combined packet is further transmitted in the network. Figure 1 illustrates the operational concept of network coding in a two-way relay

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channel (TWRC) system model. The first system model shown in Fig. 1a is without NC. Nodes 1 and 2 are not allowed to transmit at the same time; therefore, it takes four time slots for messages w_1 and w_2 to be exchanged between the two users. In Fig. 1b, Nodes 1 and 2, much like in Fig. 1a, transmit at orthogonal times. However, the relay, *R*, generates a combined message, w_{NC} , using w_1 and w_2, and sends w_{NC} in a single time slot back to both Nodes 1 and 2. The bitwise XOR is typically the operation that generates W_{NC} (i.e., $W_{NC} = w_1 \oplus w_2$). In downlink (DL), each of these nodes performs a similar operation on W_{NC} by XOR'ing that with a copy of what was sent previously (i.e., $w_1 \oplus W_{NC}$ for Node 1 and $w_2 \oplus W_{NC}$ for Node 2) to extract the actual packet sent by the other node. In Fig. 1c, Nodes 1 and 2 can transmit at the same time. Since messages w_1 and w_2 interfere at *R*, decoding or separating each from the other may not be possible. This is the reason wireless communication systems employ orthogonal multiple access schemes in either time, frequency, space, or code to reduce the effects of interference. However, this interference becomes trivial through NC at the physical-layer since it generates or maps interfered symbols to network-coded (also NC) symbols. The NC symbols are chosen such that there is no ambiguity for each node to recover its intended messages from others. Upon receiving the broadcast DL NC symbols, each node performs a similar operation to retrieve the symbols sent by the other transmitting nodes. Irrespective of the chosen modulation scheme at the physical layer, the constellation of the superimposed signals at the relay may go out of range if compared to the constellation of the modulated signals at the transmitting nodes. Therefore, a key challenge in PNC is the development of unambiguous PNC mapping algorithms that map superimposed constellations at the relay to the constellations that can be decoded by each node. The toleration of interference in PNC leads to capacity boost, as the number of time slots that are required to complete the end-to-end communication in a relay system is reduced by half.

Massive multiple-input multiple-output (MIMO) [6] is another promising physical-layer technology that is known to exploit a large array of antennas to strengthen the capability of spatially multiplexing many user terminals in the same time-frequency resource, which yields higher channel capacity and higher throughput gains. Leveraging on the multiplexing gain, a joint massive MIMO and PNC scheme has been shown to yield explosive capacity gains [7–9]. For example, a practical approach of combining PNC and massive MIMO is investigated in [9]. The bit error performance, as shown in Fig. 2, revealed that at twice the SE, massive MIMO with PNC has lower error performance compared to conventional massive MIMO (without PNC), indicating that PNC can be deployed in massive MIMO systems without necessarily degrading the latter.

In a two-way relay communication system, since PNC requires only two time slots for end-to-end communication between the two nodes, as opposed to four time slots in conventional interference-free communication systems, the reduction in time addresses the latency requirements of URLLC to some degree by reducing the latency.

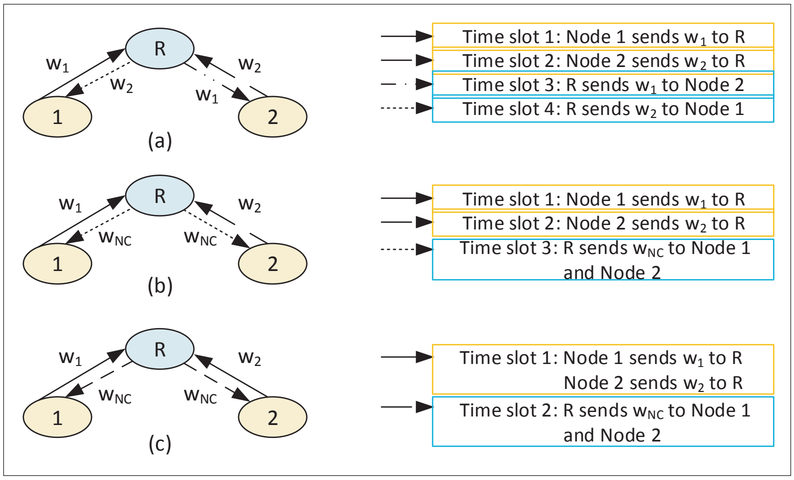

FIGURE 1. Network coding in TWRC.

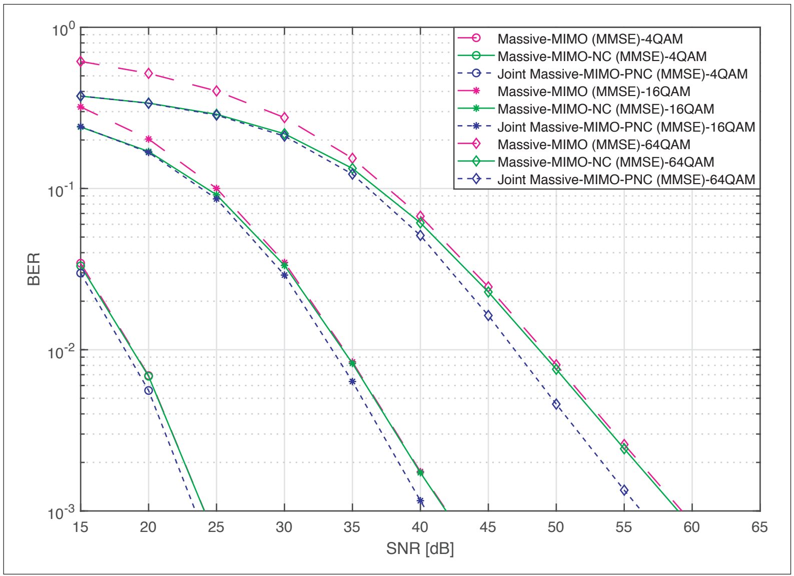

FIGURE 2. BER performance comparison between a) 128 × 128 conventional multi-user massive MIMO; b) 128 x 128 multi-user massive MIMO with jamming; c) 128 x 128 multi-user massive MIMO with PNC; d) multi-user MIMO with PNC.

INDEX MODULATION

IM is a promising technique for 5G and beyond [10]. While the current wireless communication systems require that any information received at the receiver is indeed a replica of what the transmitter has sent, IM has found innovative ways to convey information from the transmitter to the receiver without the information necessarily being transmitted. Rather, IM uses the indices of the resources to convey extra information bits. There is a growing need for techniques that offer a compromise between higher SE and EE to be those that are considered in 5G and beyond, and IM shows promising gains in both metrics. The resources on which IM operates include sub-carriers, modulation types, time slots, and transmit antennas among others [11].

IM introduces an additional dimension to the existing dimensions of wireless transmission that include space, time, and frequency. By not using all the available resources to transmit, communication systems can be designed at lower cost, lower hardware complexity, and reduced energy usage, as few of the resources are actively utilized

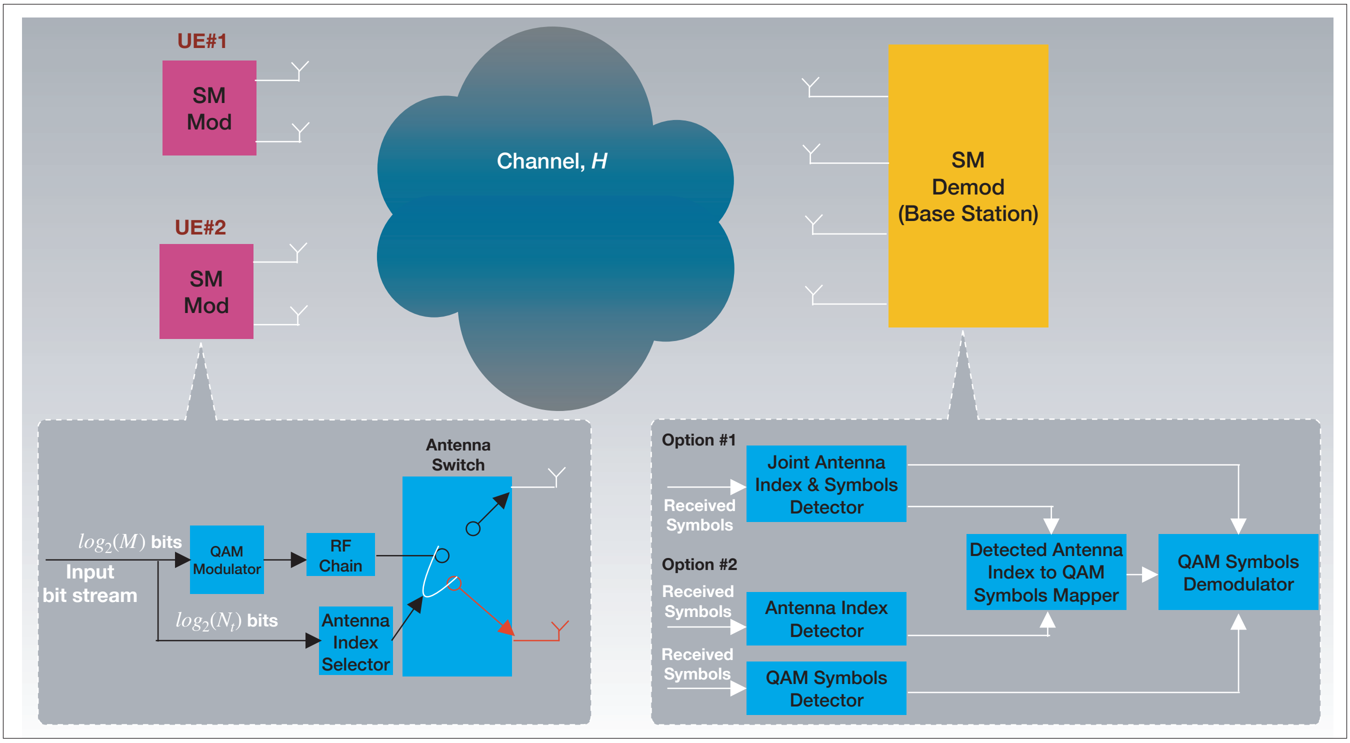

FIGURE 3. Functional blocks of a multi-user SM MIMO communication system.

Bits block	Antenna index	Tx symbol
00	1	–1
01	1	1
10	2	–1
11	2	1

TABLE 1. SM mapping of 4-QAM bit block to antenna index and 2-QAM symbol.

at any time, while simultaneously guaranteeing high SE and capacity gain.

One of the well researched variants of IM is spatial modulation (SM), and it is the main focus of the next section.

SPATIAL MODULATION

While conventional MIMO communication systems leverage on the ability to use all the transmit antennas to increase multiplexing gain by simultaneously transmitting data on all of them, SM, on the contrary, allows transmission over a single antenna. The stream of data to be transmitted is divided into two groups. One group decides which antenna is selected for transmission, and the other group is transmitted on the selected antenna. The receiver will detect not only the transmitted data, but also the index of the transmit antenna used for the transmission. MIMO systems usually require one RF chain for each antenna element to be designed at the transmitter. However, such a design is costly, especially when a massive number of antennas are to be implemented. There have been greater strides in mitigating this cost with a blend of digital and analog designs [12]. However, in SM, since only a single antenna is activated at any time, only a single RF chain is needed.

To illustrate how SM works, let us take Fig. 3 as an example. In this figure, there is a base station (BS), with four antennas, communicating with two user equipments (UEs), each equipped with two antennas. To increase capacity in MIMO communication systems, the UEs would have to exhaust all their transmit antennas to send multiple data streams to the BS. Considering that battery-powered communication devices, such as mobile phones, have limitations on the number of antennas they can be equipped with, it is not scalable and practical that by virtue of wanting to increase multiplexing gain, the number of antennas is increased. Assuming that the UEs will use quadrature phase shift keying (QPSK)/4-quadrature amplitude modulation (QAM) to transmit the bit blocks, using SM, the QPSK bit block will be split into two: one that identifies the antenna that will be selected for transmission, and the other the actual transmitted bits. For example, in Table 1, for QPSK bit block 01, bit 0 identifies antenna number one, and bit 1 is mapped to 1 binary phase shift keying (BPSK) constellation symbol and transmitted on the selected antenna. This inadvertently results in a spectral efficiency of 2 b/channel use/user, one coming from the antenna index and the other from the BPSK symbol, although only a single bit is transmitted.

The main challenge with SM is the detection of the implicitly transmitted antenna index at the receiver or BS. In order to detect the selected antenna for each user, although nothing is transmitted on the non-selected antennas, it is still imperative that all antennas are active. It is also important that the BS assumes the totality of both the selected and non-selected antennas for the SM. Figure 3 illustrates the building blocks that handle the received messages with the assumption that the transmitting nodes use SM. Joint detection of the antenna index and the

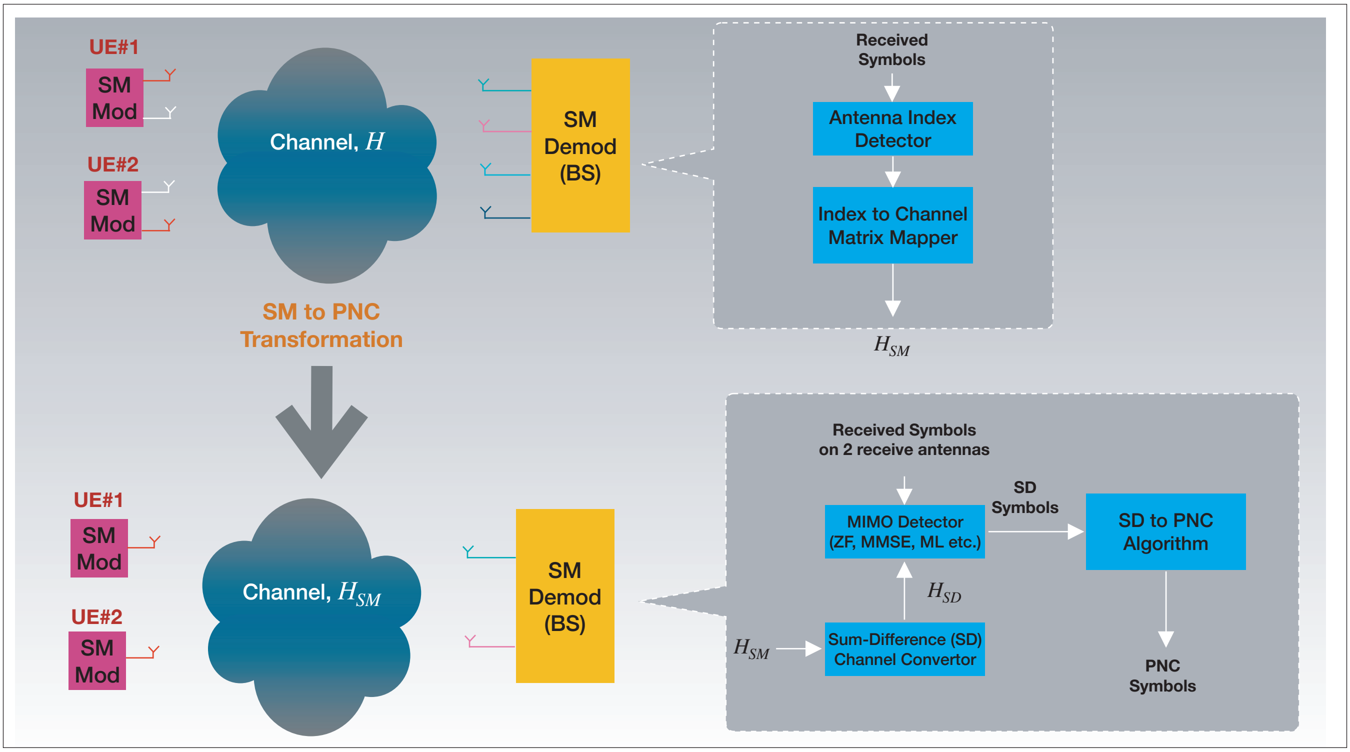

Figure 4. Functional blocks of a joint multi-user SM MIMO PNC communication system.

transmitted symbols is usually the most common approach. Here, both the antenna index and the transmitted symbols can be detected at the same time using a maximum likelihood (ML) estimator. The detected antenna index can then further be decoded by mapping it to the corresponding symbol that was implicitly transmitted. The other alternative will be to use ML to detect the antenna index and use other practical detectors such as zero-forcing (ZF) and minimum mean square error (MMSE) to detect the transmitted symbols. Similar to the joint antenna index and transmitted symbol detection approach, the antenna index is further decoded by mapping it to the implicitly transmitted symbols. In Fig. 3, using two antennas, each transmitter is able to transmit QPSK symbols by splitting them into two BPSKs, one that identifies the antenna index and the other physically transmitted on the selected antenna. By detecting the antenna index, the receiver is able to infer the corresponding bits or symbol at the transmitter. This implicit transmission of the symbols for the antenna index increases EE, as half of the energy required to transmit QPSK is needed in SM.

While PNC addresses the latency requirement of URLLC, IM addresses the EE requirement of critical machine-type communications (cMTC) applications that fall under the URLLC use case, such as wearable sensors in the healthcare industry [13], which run on limited capacity of power supply.

Joint Physical Layer Network Coding and Spatial Modulation

The wireless communication era beyond 5G will be augmented by novel enabling technologies. However, it is expected that a mix of existing technologies will be in place to satisfy the crunching requirements of beyond 5G communications. A joint IM-PNC or SM-PNC is an attractive combination, as each has their unique characteristics, with one complementing the other. For example, SM eliminates inter-channel interference (ICI), whereas PNC embraces ICI. The challenge here will be combining these techniques.

In [9], we showed how PNC and massive MIMO can be combined and the benefits they present. To combine massive MIMO PNC with IM/SM, assuming nothing changes in the architecture of MIMO-IM, as described in the previous section, then, in uplink, depending on the QPSK bit block, each user uses the first bit to select an antenna and transmits the other half of the bit block on the selected antenna. Since in PNC there is the need to estimate PNC symbols, without necessarily decoding the individual transmitted symbols, detecting the antenna index alone is sufficient. In [9], once the receiver knows the channel state information, $\boldsymbol{H}$, our PNC algorithm will first estimate the sum-difference (SD) of the transmitted symbols and then use the PNC mapping algorithm [9] to estimate PNC symbols from the estimated SD symbols. In the case of the SM, the channel, $\boldsymbol{H}$, cannot be directly used by the PNC algorithm, because the algorithm operates on the symbols that have been physically transmitted. For SM, the BS perceives the uplink as a multiplex of single-channel transmissions per user. Therefore, there is a need for a transformation from two-antenna UEs to one-antenna UEs, and this transformation requires that the channel, $\boldsymbol{H}$, is transformed as well. The transformation of the original channel, $\boldsymbol{H}$, in SM can be achieved by first detecting the antenna index used for transmission. Knowing the antenna index, from the original channel, $\boldsymbol{H}$, the columns not related to the antenna index can be masked out, and the resulting SM channel is $\boldsymbol{H}_{SM}$. $\boldsymbol{H}_{SM}$ is then further transformed into the SD chan-

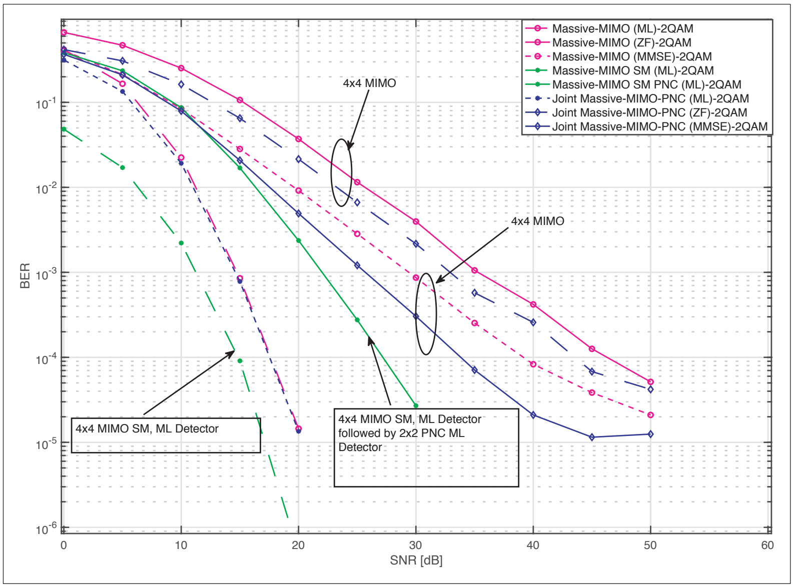

FIGURE 5. Simulation results of a 4 × 4 MIMO system that uses SM to estimate PNC symbols.

nel, $\boldsymbol{H}_{SD}$, and the latter is the channel matrix on which our PNC algorithm operates.

In Fig. 5, a 4 × 4 MIMO system was simulated using spatial modulation. In this setup, each user has two transmit antennas, and the BS has four antennas. Each user transmits using QPSK modulation, and at any transmit time, because of SM, only a single antenna is utilized. At the receiver, the BS estimates the PNC symbols from the QPSK-based SM transmitted symbols using the building block in Fig. 4. The simulation results in Fig. 4 reveal that it is indeed feasible to combine PNC and SM, where the EE is significantly reduced. The error performance results indicate that the joint MIMO-SM-PNC does perform better than the other PNC schemes, but performs a little poorly against the MIMO-SM. The reason could be attributed to the fact that in the MIMO-SM, the individual symbols are detected, whereas with MIMO-SM-PNC, the antenna index is rather detected to formulate the channel matrix that should be used in the PNC algorithm.

While neither PNC nor IM/SM nor the joint MIMO-SM-PNC addresses the reliability requirements of URLLC, our simulation results reveal that the performance of the joint MIMO-SM-PNC does not deteriorate below the performance of the underlying MIMO system, guaranteeing that reliability performance will not be adversely impacted by our novel MIMO-SM-PNC scheme.

CONCLUSIONS

In this article, we present a novel approach for combining PNC and SM, a variant of IM. Individually, each of these physical-layer techniques offer compelling performance benefits that foster a good balance between the EE and SE. PNC leverages on interference from different transmitters to provide high capacity gain and also increases SE, whereas IM/SM uses few available resources to achieve the same capacity as if all resources were utilized, leading to higher EE. We present simulation results of the combined techniques, and although the performance is good, it still requires further research to make it as practical as possible by finding practical detection techniques that are able to jointly detect antenna index and generate the PNC symbols with little or no loss in information.

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