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Editorial

La revista $\mathcal{DIFU}_{100}ci@$ es una revista cuatrimestral que comenzó su publicación oficial en 2005. En mayo del 2012, la revista $\mathcal{DIFU}_{100}ci@$ adquirió el ISSN.
Desde entonces, se pretende contribuir a la difusión del conocimiento de la comunidad académica tanto nacional como internacional mediante la difusión de resultados de investigación de alta calidad. La Revista se centra en obras originales, que incluyen principalmente los estudios experimentales, análisis numéricos, estudios de casos y revisiones bibliográficas que proporcionan una significativa contribución a las áreas de ingeniería y tecnología en todas las disciplinas (Electrónica, Eléctrica, Ciencias de la Computación, Mecatrónica, Robótica, Telecomunicaciones, Procesamiento de señales, Ingeniería Industrial, Ingeniería de Control, y Bioingeniería).

Desde el comienzo, la revista ha buscado la mejora de los artículos aceptados para su publicación por un proceso de evaluación por pares o árbitro de los manuscritos recibidos. Estas evaluaciones son llevadas a cabo por expertos de reconocido prestigio por sus conocimientos y logros académicos, con el objetivo de asegurar que las publicaciones seleccionadas están contribuyendo al estado del arte en diferentes áreas de interés. Además, desde su inicio, la revista se ha abierto a los estudiantes y académicos a través del Sistema Open Journal, facilitando todo el proceso de presentación y publicación.

Agradezco a los autores y revisores, que se esfuerzan para mejorar la calidad de los manuscritos. Exhorto a todos los investigadores, académicos y estudiantes en las áreas de ingeniería y tecnología para que continúen sometiendo sus artículos en nuestra revista y contribuir a la noble difusión de la ciencia y la tecnología.

Jorge Flores Troncoso
Editor en Jefe, Revista $\mathcal{DIFU}_{100}ci@$
Universidad Autónoma de Zacatecas

A Comparative Performance Analysis for Spatial Modulation (SM) and Quadrature-Amplitude Modulation (QAM) Techniques

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Abstract

Spatial modulation is a novel technique for the transmission of signals through a system of multiple antennas known as Multiple Input-Multiple Output (MIMO), where the index of the transmit antenna is used as an additional source of information to improve the overall spectral efficiency. In this paper, we use space shift keying (SSK), which is the simplest form of spatial modulation, to present a comparative performance analysis against the existing and well-known method of quadrature amplitude modulation (QAM). In order to carry out this analysis, this paper compares the bit error rate (BER) performance between SSK and QAM transmission schemes and computes their detection complexity at the receiver in terms of floating point operations (flops). Simulations results show that SSK achieves BER performance gains of up to 7 dB compared to QAM. In terms of detection complexity, SSK has a reduction of up to 33 % for the analyzed cases.

Keywords: Spatial modulation, MIMO, SSK, BER, flops.

1. Introduction

Digital modulation is a process that prints a digital symbol on a suitable signal for transmission through a wired or wireless medium in order to receive an error free demodulated signal on the receiver side [1]. Among the well-known modulation techniques implemented for transmission of information in current systems without the use of multiple antennas are Quadrature Phase Shift Keying (QPSK) and Quadrature Amplitude Modulation

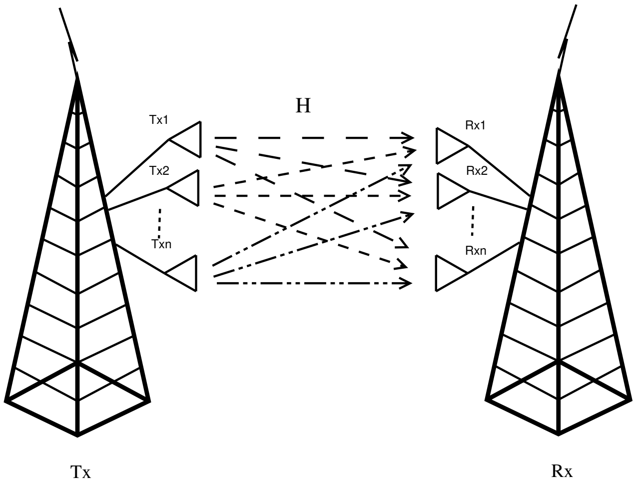

Figure 1. The MIMO transmission system.

(QAM) modulation techniques, which have also been proposed to be used in the fourth generation of long term evolution (4G-LTE) and WiFi networks. On the other hand, modern networks consider the use of multiple input-multiple output (MIMO) systems to increase the capacity and their overall performance. The term MIMO refers to a communication system with multiple transmit (Tx) and receive (Rx) antennas. Fig. 1 shows the conceptual transmission/reception scheme of a MIMO system.

As an emerging MIMO technology, spatial modulation (SM) has shown the potential of improving the performance as compared to the conventional modulation techniques [2] [3]. The most basic SM scheme, called space shift keying (SSK), carries information by only using the indices of the Tx antennas. In SSK, only one Tx antenna is activated to transmit a signal at a time, while the rest of the Tx antennas remains off. Recently, SM and SSK systems have been considered part of the so called "index modulation" (IM) techniques [4]. The main difference between SM and SSK schemes is that in SM the Tx antenna is activated using a QAM symbol while in SSK the Tx antenna is activated using only the RF signal [5] [6].

Recently, new transmission schemes based on SM/SSK have been proposed. In [7], maximum combination spatial modulation (MCSM) scheme is used to optimally determine the required number of active Tx antennas. As a result, the BER performance is improved. More importantly, some of the current potential applications of SM based transmission schemes include visible light communication (VLC) [8] and vehicle to vehicle (V2V) communication systems [9].

In order to evaluate the performance the of spatial constellation, in this paper a comparison between SSK and QAM modulation techniques is presented in terms of BER and detection complexity. Simulations results show that SSK achieves BER performance gains of up to 7dB compared to QAM. In terms of detection complexity, SSK has a reduction of up to 33.

The rest of the paper is organized as follows; Section 2 briefly describes a general MIMO system model. In Section 3, the SSK transmission scheme is described. An analysis of detection complexity for M-QAM and M-SSK techniques is carried out in section 4. The comparative performance in terms of BER is presented in section 5. Finally, section 6 concludes the paper.

2. MIMO system model

In general, the mathematical model for MIMO systems is defined as

$$\mathbf{y} = \sqrt{\rho}\mathbf{H}\mathbf{x} + \mathbf{n}, \tag{1}$$

where $\mathbf{x} \in \mathbb{C}^{N_t \times 1}$, is the transmitted signal vector, $\mathbf{y} \in \mathbb{C}^{N_r \times 1}$ is the received signal vector, $\mathbf{H}$ is the channel matrix of size $N_r \times N_t$ defined as

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & \dots & h_{1N_t} \\ h_{21} & h_{22} & h_{11} & & h_{11} \\ h_{31} & h_{32} & h_{33} & & \vdots \\ \vdots & & & \ddots & \\ h_{N_r1} & h_{N_r2} & & & h_{N_rN_t} \end{bmatrix} \tag{2}$$

with N_t as the number of Tx antennas, N_r as the number of Rx antennas and ρ is the signal to noise ratio (SNR) at the receiver. Without loss of generality, a Rayleigh flat fading channel is assumed which has independent Gaussian inputs with zero mean and unit variance. The vector $\mathbf{n} \in \mathbb{C}^{N_r \times 1}$ is the additive white Gaussian (AWGN) noise at the receiver.

2.1. Modulation techniques

Two of the the most used modulation techniques in conventional MIMO wireless communications are quaternary phase shift keying (QPSK) and quadrature amplitude modulation (QAM) [10]. QPSK is a type of angular, constant-amplitude digital modulation. With QPSK, four output phases are possible for a single carrier frequency. Since there are four different output phases, there must be four different entry conditions. In this way, $m = \log_2(4) = 2$ bits are required to encode the output. Consequently, in the QPSK, the input binary data are combined in groups of two bits, *i.e.* {00, 01, 10, 11}. Each combination generates one of the four possible output phases. On the other hand, QAM modulation scheme can be seen as a generalization of QPSK.

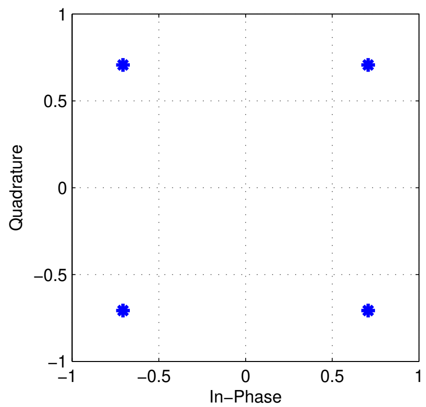

Figure 2. 4–QAM Constellation.

It is based on the amplitude and phase symbols manipulation in order to modulate an input signal. The more basic M–ary QAM communication scheme is the 4–QAM, which is a rotated version of a QPSK constellation. Fig. 2 shows the corresponding constellation diagram for 4-QAM. The output 4–QAM symbols are defined in Table 1.

Table 1. 4–QAM modulation.

Input bits	Symbols	4–QAM Symbols
00	S_1	$+\frac{1}{\sqrt{2}}+\frac{1}{\sqrt{2}}j$
01	S_2	$-\frac{1}{\sqrt{2}}+\frac{1}{\sqrt{2}}j$
10	S_3	$-\frac{1}{\sqrt{2}}-\frac{1}{\sqrt{2}}j$
11	S_4	$+\frac{1}{\sqrt{2}}-\frac{1}{\sqrt{2}}j$

2.2. Optimal ML detection

As the transmitted signal reaches the receiver, it recovers the signal using a detection algorithm. In this paper, the optimal criterion of maximum likelihood (ML) is considered for detection [9]. This detector performs a brute force search comparing the received signal with a lattice of all possibilities in each Rx antenna. The ML detector criterion is defined as

$$\hat{\mathbf{x}} = \arg\min_{j} \|\mathbf{y} - \sqrt{\rho}\mathbf{H}\mathbf{x}_j\|^2. \quad (3)$$

where $\mathbf{x}_j \in \mathbb{C}^{N_t \times 1} = \{s_1, s_2, \cdots, s_{N_t}\}$ is a combination of all possible M-QAM transmitted signals.

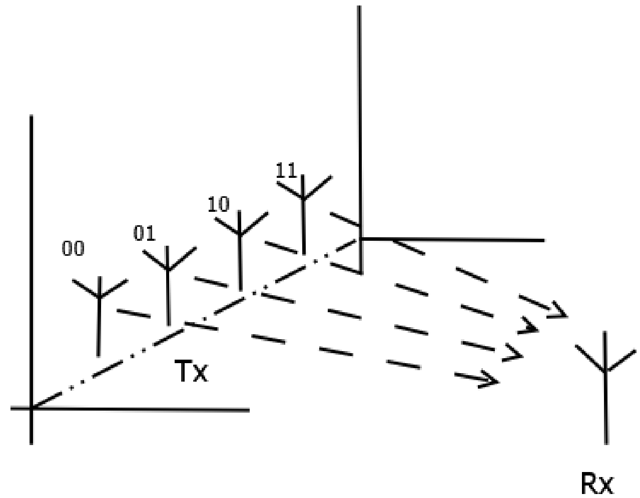

Figure 3. 4–SSK Constellation, $m = 2$.

3. M–SSK System model

The basic idea of SSK is to consider an array of Tx antennas as an spatial constellation where each Tx antenna is independently activated to select one of the spatial constellation points. In SSK, the transmission of bits emitted by a binary source are divided into blocks. Each block contains $m = \log_2(N_t)$ bits. The modulation M–SSK requires that $N_t = M$ [5]. Fig. 3 shows an example of SSK with an array of $N_t = 4$ antennas. As shown in Table 2, the transmission vector $\mathbf{x}^T$ has only one position different from the zero vector in the 16-SSK constellation. The SSK mechanism can be seen as a channel selector in the transmission.

Table 2. SSK Mapping example with $m = 4$.

$a = [a_1, a_2, a_3, a_4]$	index	$\mathbf{x}^T = [x_1, x_2, \cdots, x_{16}]$
0 0 0 0	1	[1000000000000000]
0 0 0 1	2	[0100000000000000]
0 0 1 0	3	[0010000000000000]
0 0 1 1	4	[0001000000000000]
0 1 0 0	5	[0000100000000000]
0 1 0 1	6	[0000010000000000]
0 1 1 0	7	[0000001000000000]
0 1 1 1	8	[0000000100000000]
1 0 0 0	9	[0000000010000000]
1 0 0 1	10	[0000000001000000]
1 0 1 0	11	[0000000000100000]
1 0 1 1	12	[0000000000010000]
1 1 0 0	13	[0000000000001000]
1 1 0 1	14	[0000000000000100]
1 1 1 0	15	[0000000000000010]
1 1 1 1	16	[0000000000000001]

The general MIMO system model in (1) is modified for the SSK scheme as follows

$$\mathbf{y}_{SSK} = \sqrt{\rho}\mathbf{h}_j + \mathbf{n}, \tag{4}$$

where $\mathbf{h}_j = \mathbf{Hx}$ is the j-th column of the channel matrix $\mathbf{H}$, assuming the transmission of symbol j from the spatial constellation.

3.1. Optimal ML detection for SSK

The received signal in SSK is the channel corresponding to the active Tx antenna. Therefore, the ML criterion for SSK becomes

$$\hat{\mathbf{h}} = \arg\min_j \|\mathbf{y}_{SSK} - \sqrt{\rho}\mathbf{h}_j\|^2, \tag{5}$$

where $\hat{\mathbf{h}}$ is the more likely used channel for all possibilities in $\mathbf{h}_j$ for $j = 1, 2, \cdots, N_t$.

4. Complexity analysis

The complexity γ of the detection algorithm is measured using the total number of floating point operations (flops) [11]. For complex additions and multiplications, 2 and 6 flops are carried out respectively, while for subtractions and divisions take the same value in flops as addition and multiplication respectively. Table 3 summarizes the value in flops for different operations between numbers with real and complex values.

Table 3. Complexity of basic operations.

Operation	*flops*
$\mathfrak{R} + \mathfrak{R}$	1
$\mathfrak{R} \times \mathfrak{R}$	1
$\mathfrak{R} + \mathbb{C}$	1
$\mathbb{C} + \mathbb{C}$	2
$\mathbb{C} \times \mathfrak{R}$	2
$\mathbb{C} \times \mathbb{C}$	6

4.1. Detection complexity of the conventional MIMO system

In a MIMO array of N_t transmit antennas and N_r receive antennas, any M-QAM symbol can be transmitted, then, a lattice $\mathcal{L} = \{l_1, l_2, \cdots, l_{M^{N_t}}\}$ of size M^{N_t} for all possible combination of the channel and the transmitted signal can be generated in the reception. For the i-th receive antenna, the elements l_q in the lattice $\mathcal{L}$ are defined as

$$l_q = \sum_{j=1}^{j=N_t}\sum_{k=1}^{k=M} h_{i,j}s_k. \tag{6}$$

Results for each receive antenna are combined using maximum ratio (MRC) in the receptor in order to guarantee the best estimation.

Considering only one Rx antenna in (3), the product $\mathbf{Hx}_j$ requires $M^{N_t}(8N_t - 2)$ flops. Multiplying by $\sqrt{\rho}$ requires $2M^{N_t}$ flops. The differences add $2M^{N_t}$ flops. The operation $\|\cdot\|^2$, requires multiplications of complex numbers which use $6M^{N_t}$ flops. The MRC adds the results of all Rx antennas using $2M^{N_t}(N_r - 1)$ flops. Finally, finding the minimum value takes $(M^{N_t} - 1)$ flops. Then, the complexity of the conventional MIMO-QAM detector is

$$\begin{aligned}\gamma_{MIMO-QAM} = {} & N_r(M^{N_t}(8N_t - 2) - 10M^{N_t}) \\ & +2M^{N_t}(N_r - 1) + (M^{N_t} - 1).\end{aligned} \tag{7}$$

Table 4 summarizes the results of complexity for each step in the detection process.

The receiver complexity γ for a single Tx antenna in the QAM system can be approximated as

$$\gamma_{QAM} = 18MN_r. \tag{8}$$

4.2. Complexity of the M-SSK system

In SSK, only one Tx antenna is activated at a time, whereas the other Tx antennas of the system will be off during one symbol transmission[2]. Then, the lattice in this case is made up of the channel values. Considering for example the first Rx antenna the lattice is

$$\mathcal{L} = \rho\{h_{11}, h_{12}, \cdots, h_{N_t}\}. \tag{9}$$

Since ρ is a real number, based on Table 3, the products $\rho\mathbf{H}$ use $2N_t$ flops for each Rx antenna. The differences

Table 4. Complexity for MIMO M-QAM.

Operation	*flops*
$\mathbf{Hx}_j$	$M^{N_t}(8N_t - 2)$
$\sqrt{\rho}\mathbf{Hx}_j$	$2M^{N_t}$
$y - \sqrt{\rho}\mathbf{Hx}_j$	$2M^{N_t}$
$\|\cdot\|^2$	$6M^{N_t}$
MRC	$N_r(M^{N_t}(8N_t - 2) + 10M^{N_t}) + 2M^{N_t}(N_r - 1)$
$\arg\min \|\cdot\|^2$	$N_r(M^{N_t}(8N_t - 2) + 10M^{N_t}) + 2M^{N_t}(N_r - 1)$ $+(M^{N_t} - 1)$

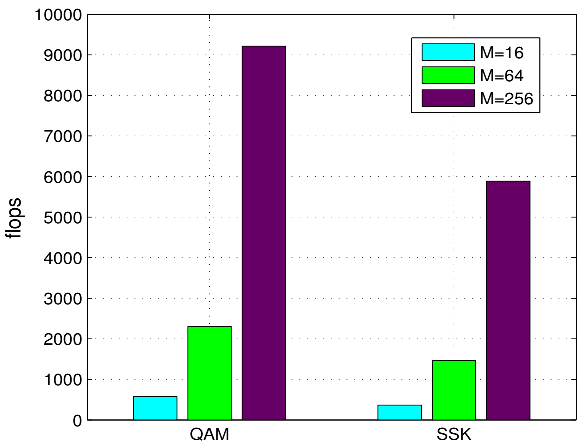

Figure 4. Complexity comparison for M-QAM and M-SSK with M = 16, 64 and 256.

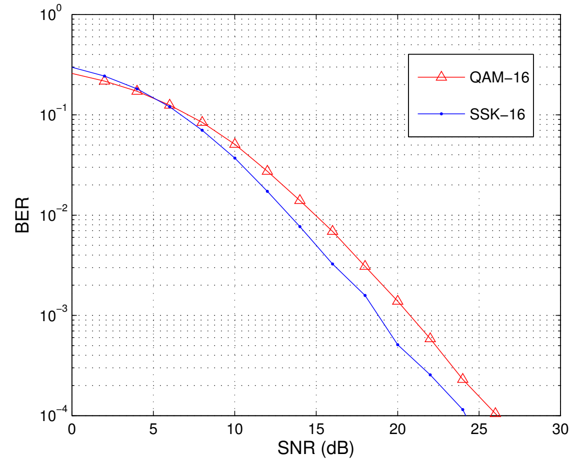

Figure 5. BER Performance comparison for QAM modulation and SSK modulation with m = 4 bpcu.

between the Rx signal and the lattice $y - \rho\mathbf{H}$ as well as its square $argmin||\cdot||^2$,use $2N_t$ and $6N_t$ flops respectively. Considering N_r Rx antennas requires to use the MRC which uses $2N_t(N_r - 1)$ flops. Finally, minimum-value search result uses $(N_t - 1)$. Then, the total detection complexity for SSK is

$$\gamma_{MIMO-SSK} = N_r(10N_t) + 2N_t(N_r - 1) + (N_t - 1). \quad (10)$$

Table 5 summarizes the used operations for SSK complexity evaluation. Adding the three first terms we obtain $10N_t$ flops plus N_t for the arg min operation, the receiver complexity of SSK system can be approximated as

$$\gamma_{SSK} = 12N_rN_t. \quad (11)$$

Table 5. Complexity for MIMO–SSK.

Operations	*flops*
$\sqrt{\rho}\mathbf{H}$	$2N_t$
$y - \sqrt{\rho}\mathbf{H}$	$2N_t$
$\lVert \cdot \rVert^2$	$6N_t$
MRC	$N_r(10N_t) + 2N_t(N_r - 1)$
$\arg\min \lVert \cdot \rVert^2$	$N_r(10N_t) + 2N_t(N_r - 1) + (N_t - 1)$

Considering only one Tx antenna for QAM and one Rx antenna for both schemes, QAM has 54 % more complexity than SSK. Fig. 4 shows a comparison of detection complexity of QAM and SSK modulation schemes for M = 4, 16, 64 and 256. Table 6 shows a complexity comparison for different scenarios.

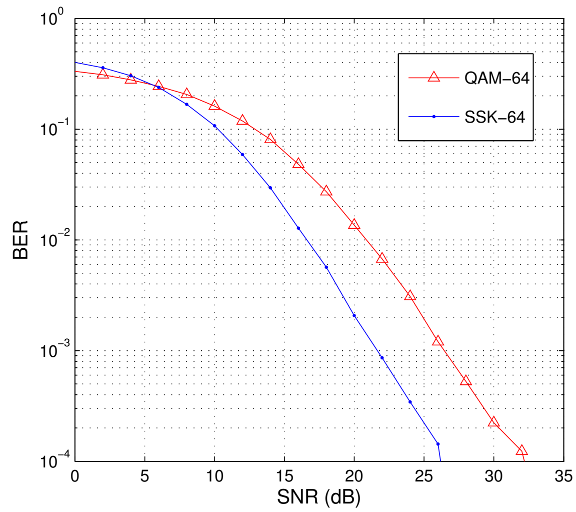

Figure 6. BER Performance comparison for QAM modulation and SSK modulation with m = 6 bpcu.

5. BER Performance results

In this section, simulations are used to compare BER performance of the spatial constellation and the conventional amplitude-phase constellation. For the conventional M-QAM, $N_t = 1$ is considered whereas $N_r = 2$

Table 6. Complexity comparison.

Scheme /γ	M=16, N_r=2	M=64, N_r=4	M=128, N_r=8
M–QAM	576	4,608	18,432
M–SSK	384	3,072	12,288

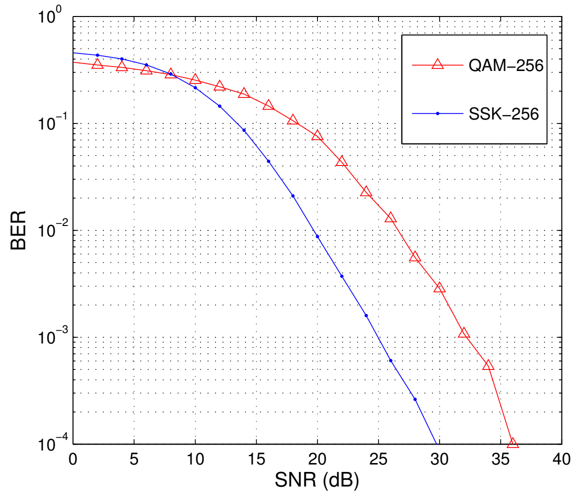

Figure 7. BER Performance comparison for QAM modulation and SSK modulation with m = 8 bpcu.

is considered for both, the M-QAM and the M-SSK schemes. We analyze the following three cases: $m = 4, 6,$ and 8 bits per channel use (bpcu).

Fig. 5 shows results of BER performance for a spectral efficiency of $m = 4$ bpcu. The SSK scheme has 2 dB gain considering an error rate of 10^{-3}. The simulation results for a spectral efficiency of $m = 6$ bpcu are presented in Fig. 6. It can be seen that SSK has 4 dB gain approximately considering an error rate of 10^{-3}. Finally, Fig. 7 presents the comparison of BER performance for a spectral efficiency of $m = 8$ bpcu. In this case, the SSK scheme has 7 dB gain approximately for the target error rate of 10^{-3}.

6. Conclusion

In this paper, a comparative analysis in BER performance and detection complexity for M-QAM and M-SSK schemes has been presented. Results show that SSK has considerable advantages over the conventional QAM scheme. Simulations results show that SSKachieves BER performance gains of up to 7 dB compared to QAM. In terms of detection complexity, SSK has areduction of up to 33 %. The main drawback of SSK, is the number of Tx antennas required for large constellations, however, it must be taken into account that in SSK, only one Tx antenna is active at a time. Also, SSK can be implemented on the novel MIMO massive systems, where the number of Tx antennas is not limited. Another consideration to take into account is the switching required in the transmitter side of SSK systems. Although this requirement supposes an additional complexity in the SSK transmitter, it allows receivers with lower complexity which is more critical in practical systems implementation.

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