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# Low-Resolution ADCs for Wireless Communication: A Comprehensive Survey

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**ABSTRACT** With the rapid growth of wireless data traffic and antennas configuration, higher spectrum efficiency and lower power consumption processing have evoked remarkable attention from the research and industry community for the deployment of future wireless communication. It has become a heated topic quickly in recent years and gives rise to the widespread interest around the world. As a core technology of the fifth-generation (5G) mobile communication, massive multi-input multi-output (MIMO) technology can fully exploit the space resources and greatly improve the spectral and energy efficiency. However, massive MIMO systems are faced with the problems of mass data processing, high hardware cost, and huge total power consumption. To cope with these problems, a useful solution is that the receiver equips with finite resolution analog-to-digital (ADC) converters. A large number of research results show that the low-resolution quantization technology brings significant performance within the allowable loss of capacity. This promising technique has attracted many scholars to do tremendous endeavor on it. As a motivation, we make a comprehensive survey about low-resolution ADCs for wireless communication. This paper summarizes the latest developments in the design of low-resolution communication systems, focusing on system performance analysis, some key technologies of the receiver, and typical application scenarios for the low-resolution ADCs. In view of the adverse effects caused by coarse quantization, some potential implementations are presented to alleviate this dilemma. Future research directions are also given and suggested in this paper. This overview contributes significantly to providing an informative and tutorial reference for the key technologies of low-resolution ADCs as well as its applications in practical systems.

**INDEX TERMS** Low resolution quantization, multi-input and multi-output, channel capacity, channel estimation, automatic gain control, synchronization, receiver, relay system.

## I. INTRODUCTION

With the ever-increasing requirements of bandwidth and antennas configuration in next generation wireless systems, the various services and applications in 5G network are deployed in a single system to satisfy high-speed access requirements for multi-user and multi-machine environment [1]. A main reason is due to the use of

millimeter-wave (mmWave) carrier frequencies in personal area networks [2], local area networks [3], and likely even cellular networks [4]. The ultra-wideband (UWB) technology is a representative of short-range wireless communication, reaching the order of hundred megahertz (MHz) or even gigahertz (GHz). Unfortunately, high-speed, high-resolution ADCs are costly and power-hungry for portable devices. Especially, the high-resolution ADCs with 10 GHz still have technical difficulties. Whether it is high-speed and large bandwidth communication system, mm Wave system or

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massive MIMO system [5], from the point of solving power assumption bottleneck, low-resolution quantized receiver is one of the most promising direct ways to realize high energy efficiency.

Compared with traditional high-resolution quantization, because the output signal of quantization with low-resolution quantizer has very large non-linear distortion [6], different quantization error models and research methods are needed for the research of low-resolution ADCs. Previous research on quantization is mainly based on the premise of high-resolution quantization. By looking at quantization process and back-end baseband processing independently, the impact of quantization resolution on system performance is analyzed through quantized output signal model [7]. From the perspective of information theory and spectrum, the loss of channel capacity and spectrum efficiency caused by 2-3 bits ADC receiver in Gaussian channel is very small [8], [9]. At 0dB, the spectrum loss of 2-bit ADC receiver is only 5% compared with the full resolution signal, and at 20dB, the spectrum loss of 3-bit ADC receiver is only 15%. This makes the application of low-resolution ADCs in communication system possible, and greatly promotes the development of wireless communication receiver technology with low-resolution quantization.

In view of the increasingly scarce spectrum resources, much research work in the field of wireless communication will also focus on the use of non-orthogonal multiple access (NOMA), filter bank multicarrier (FBMC) and sparse code multiple access (SCMA) to improve spectrum efficiency of the system [10]. With the development of high-speed communication technology, people begin to pay more attention to the energy efficiency of mobile communication system while investigate how to improve the spectral efficiency of the system. It is of great significance to realize efficient, safe, green and intelligent wireless communication in the future. As shown in Figure 1, the future 5G communication network must be a green network, where the relay systems and cellular networks will be equipped with low-resolution ADCs to reduce carbon footprint [11]. Spectral efficiency and energy efficiency will be the key indicators to measure the wireless communication system. There is no doubt that the low-resolution quantization technology will also play an important role in the future 5G communication network.

Recently, the application of low-resolution ADCs in the context of millimeter waves was reviewed in [12]. Their work is mainly carried out in six aspects: performance considerations, channel estimation, signal detector, channel information feedback, transmit precoding and mixed-ADC architecture. In their review, they discussed a variety of key physical-layer signal processing techniques, and explored the associated challenges and potential implementations of the practical 5G mmWave massive MIMO system with ADC quantizers. Their work provided a very useful insight into the practical implementation of a mmWave system with low-resolution ADCs. Different from [12], we comprehensively reviewed the development process of low-resolution

ADCs. In our work, we start with two quantized output channel models and discuss some signal processing techniques and challenges. In addition, we use hardware impairment as an entry point to explore three typical application scenarios for low-resolution ADCs. Finally, we summarize the open issues that we will face in the future and give some recommendations. In other words, our work can also be seen as an extension of [12].

The main contribution of this manuscript is as follows. In this paper, an overview of numerous existing publicly reported literatures regarding low-resolution quantization utilized in wireless receiving processing is presented. The technical restrictions and challenges concerning wireless receiving systems assisted by low-resolution quantization theory and massive MIMO technology are deeply analyzed for providing enlightening discussion and investigation guidance. The main contents of this paper are given as follows.

- 1) Review of principles of low-resolution quantization theory for additive white Gauss noise (AWGN) output channel model and additive quantization noise output channel model (AQNM).
- 2) Analyzing the existing literature pertaining to wireless receiving processing assisted by low-resolution ADCs and massive MIMO.
- 3) The development prospects and challenges of low-resolution ADCs are demonstrated in some typical application scenarios.
- 4) Recommendations on a series of research point including low-resolution quantification theory areas and application areas.

In this paper, from our perspectives, the related work with low-resolution quantization can be categorized into three types, including system performance analysis under low-resolution quantization, specific signal processing methods, and typical application scenarios for low-resolution ADCs respectively. We first start with the system performance analysis from two quantized output channel models, AWGN and AQNM, carefully discuss the effects of low-resolution ADCs on the system. Second, the related technical literatures regarding low-resolution ADCs applied in wireless receiving processing are overviewed, involving automatic gain control (AGC), synchronization, channel estimation, signal detection and receiver design. Then, the development status and beneficial effects of low-resolution ADCs are described in the application scenario of relay systems, UWB systems, and massive MIMO mmWave systems. Finally, some general and specific limitations, technical challenges, potential implementations and a series of meaningful research directions of low-resolution quantization scenario in signal processing for wireless communication are discussed.

The reminder of this paper is structured as follows. Section II gives a discussion on the principle of quantized output channel model theories of AWGN and AQNM. The capacity and performance of massive MIMO channel under low-resolution quantization are also presented. Section III

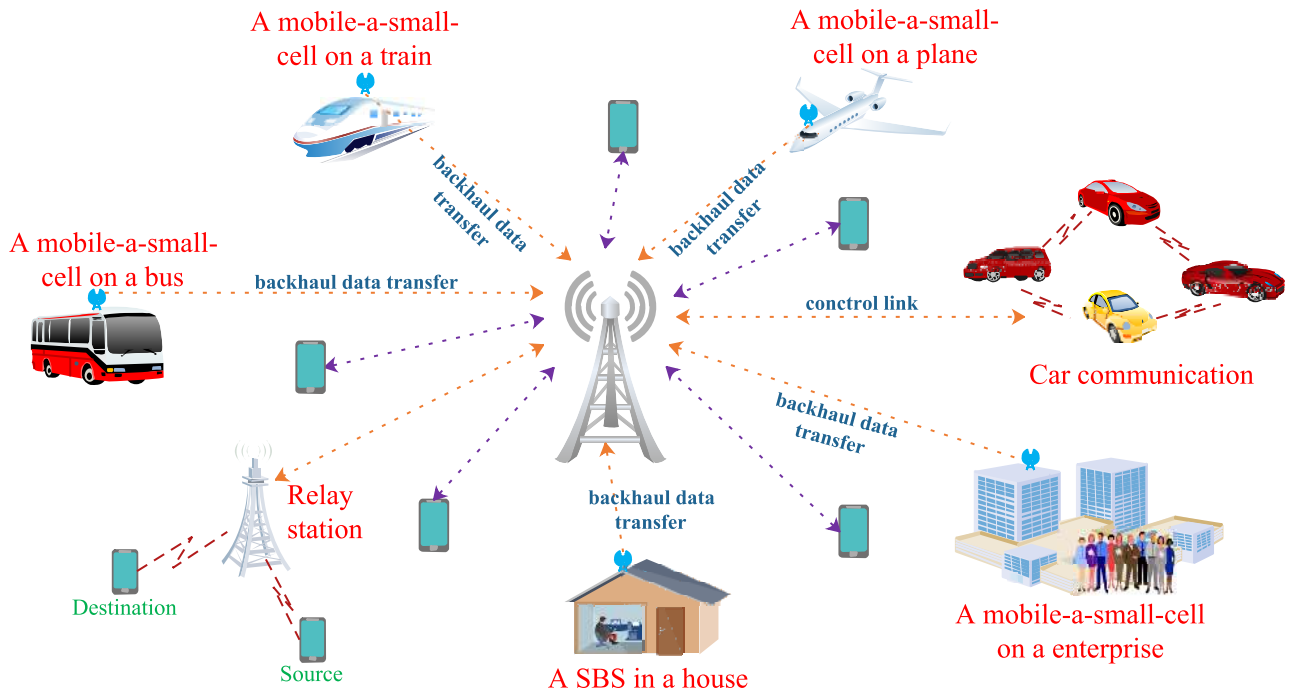


FIGURE 1. A multi-tier architecture for 5G networks with small-cell base-stations (SBS), mobile small-cells and relay networks communications.

talks about the AGC, synchronization, channel estimation, data detection and receiver design. In section IV, the impact of hardware impairments on the system is first introduced, then the advantages and latest research progress of low-resolution ADCs are discussed in the application scenario of relay systems, UWB systems, and massive MIMO mmWave systems, which is intended to show the typical applications of low-resolution ADCs. In section V, some general and specific limitations, technical challenges, potential implementations and a series of meaningful research directions of low-resolution ADCs in wireless receiving processing are expounded. Finally, conclusion is achieved in section VI. Symbols and abbreviations are presented in this paper which will be summarized in Tables 1 and 2 respectively.

**II. PERFORMANCE CONSIDERATIONS OF MASSIVE MIMO SYSTEM WITH LOW-RESOLUTION ADCs**

In this section, the process of analog-to-digital conversion is presented. Then, the two output channel models under low-resolution quantization are introduced. Based on these two models, the system performance is analyzed and summarized. In addition, some meaningful research directions are given. The detailed contents are scheduled as follows. In subsection A, the structure and applications of ADC is described. The quantized output channel models are derived in subsection B. The performance analysis based on AWGN and AQNM is discussed in subsection C. Subsection D presents some methods for improving the overall performance of the system from the perspective of the receiver architecture. Finally, the summary and some open issues of low-resolution quantization systems are given in subsection E.

TABLE 1. List of symbols.

$Y$	AWGN channel output
$\hat{Z}$	AQNM channel output
$P$	Transition probability matrix
$N$	Gauss noise with $N(0, \theta^2)$
$R$	Correlation matrix
$F$	Coefficient matrix
$C$	Channel capacity
$H$	Channel matrix
$I$	Identity matrix
$\Delta$	Quantization step
$b$	Quantization bit
$e$	Independent additive quantization noise
$\rho$	Quantization distortion factor
$q$	Quantization error
$Q(\cdot)$	Quantized function
$I(\cdot)$	Mutual information
$\mathcal{Q}(\cdot)$	Complementary Gauss distribution function

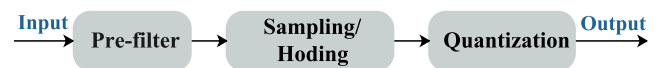


FIGURE 2. Structural model of ADC.

**A. THE PRINCIPLE AND APPLICATIONS OF ADC**

ADC is a key part of wireless receiver and can convert analog signals into discrete digital signals to facilitate subsequent data processing and storage. The schematic diagram of ADC is shown in Figure 2.

TABLE 2. List of abbreviations.

ADC	Analog-to-digital converter
AF	Amplify and forward
AGC	Automatic gain control
AQNM	Additive quantization noise model
AWGN	Additive white Gauss noise
BA	Bit allocation
BER	Bit error rate
BPSK	Binary phase shift keying
BS	Base-stations
CEM	Constant envelope modulation
CFO	Carrier frequency offset
CRLB	Cramer-Rao lower bound
CSI	Channel state information
DSP	Digital signal processing
EM	Expectation maximization
FBMC	Filter bank multicarrier
FDD	Frequency division duplex
GAMP	Generalized approximate message passing
IF	Intermediate frequency
IR	Impulse radio
LMMSE	Linear minimum mean square error
MAP	Maximum a posteriori probability
MIMO	Multiple input multiple outputs
ML	Maximum likelihood
MMSE	Minimum mean square error
mmWave	Millimeter wave
MRC	Maximal ratio combining
MRT	Maximum ratio transmission
MU-MIMO	Multisuser multiple input multiple outputs
NOMA	Non-orthogonal multiple access
OFDM	Orthogonal frequency division multiplexing
PAM	Pulse amplitude modulation
PN	Pseudo-noise
PSK	Phase shift keying
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase shift keying
RF	Radio frequency
SBS	Small-cell base-stations
SCMA	Sparse code multiple access
SDMA	Space division multiple access
SIMO	Single input multiple outputs
SISO	Single input single output
SINR	Signal to interference plus noise ratio
SNR	Signal-to-noise ratio
SQNR	Signal-to-quantization-plus-noise ratio
STO	Symbol time offset
SVD	Singular value decomposition
TDD	Time division duplex
UWB	Ultra-wideband
VG-LNA	Variable gain low-noise amplifier
ZF	Zero forcing



FIGURE 3. ADC equivalent quantization model.

process is carried out, which can filter out the signal components outside the useful frequency band and effectively prevent the aliasing of the back-end sampled signal. Then it enters the sampling/holding circuit, which can hold the sampled value after sampling the analog signal for a certain period of time. Finally, the quantization and coding process, which converts the fixed level maintained after sampling into a series of required digital codes, defines the time used in the quantization process as the conversion time.

Quantization process is the core of ADC. Its essence is to convert the sampled discrete analog value into the digital signal needed for subsequent processing. In the dynamic range of ADC circuit, the analog values belonging to the same interval are always converted to the same digital value. The binary value of this output is the quantized output. We know that different input values may output the same value after quantization, so it is obvious that there must be an error between output and input, which is also called quantization noise. Quantization methods can be divided into uniform quantization and non-uniform quantization. The quantization intervals of each stage of uniform quantization ADC are the same. Assuming that the sampled signal before quantization is described as  $X$  and the output of the quantization is expressed as  $Y$ . The system structure can be simplified as shown in Figure 3. Without losing generality, we adopt the uniform quantization method and normalize the input signal, so the signal-to-quantization noise ratio (SQNR) of the output signal can be represented by [13].

$$SQNR_{dB} = 6.02N + 10\log_{10}(12 \times \sigma_x^2) \quad (1)$$

where  $N$  represents the quantized bit of ADC, and  $\sigma_x^2$  represents the mean square difference of the input signal.

From the perspective of ADC commercial development, Texas Instruments, Analog Devices and other companies are the main suppliers of ADC chips at present. China is the world's leading demand side for ADC chips. However, there are very few companies in the world that can produce high-resolution ADC chips. Even if they do, their performance and price will not keep pace with the market. Excellent performance of ADC chips is reflected in high resolution, low power consumption, conversion efficiency and other indicators, but the shortage of resources for temperature sensors and high resolution oscillators limits the manufacture of ADC. Moreover, fewer than ten enterprises in the world can produce high performance-price ratio and high-resolution ADC chips, and most of them are American ones. In recent years, with the development of science and technology, ADC chips have been applied in many fields, such as artificial intelligence, cloud computing, 5G communication, Internet of Things, etc. There are many types of ADC, which are generally classified into six categories according to different

The ADC structure generally includes four parts: pre-filter, sampling and holding, quantization and coding. Before the analog signal is input into ADC, the front-end pre-filtering

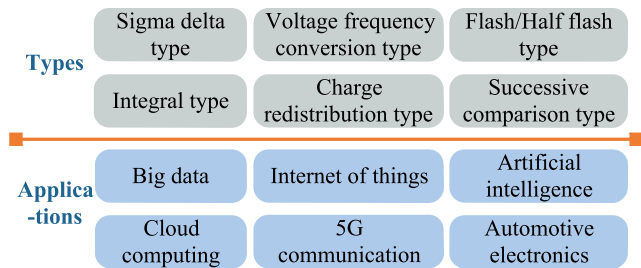


FIGURE 4. Types and applications of ADC.

working principles. The types and some applications of ADC are shown in the Figure 4. For wireless communication systems, due to the complex manufacturing process, high cost and huge power consumption of high-resolution ADCs, it is a wise choice to make the system equipped with low-resolution ADCs.

In general, since the ADC implements a conversion between an analog signal and a digital signal, the pressure of subsequent signal processing is alleviated. However, the manufacturing process of ADC with high resolution and high sampling rate is extremely complex, and the cost of a massive MIMO system equipped with high-resolution ADCs is very expensive. Therefore, the development of massive MIMO systems with low-resolution ADCs has significantly meaningful for cost reduction.

**B. QUANTIZED OUTPUT CHANNEL MODELS**

**1) ADDITIVE WHITE GAUSS NOISE OUTPUT CHANNEL MODEL**

According to the relevant theory of information theory, the channel can be divided into two types: discrete channel and continuous channel. The channel transmitting the discrete source is called a discrete channel. Suppose the input of the system is  $X = x_1, x_2, \dots, x_N$ , the probability of transmitting the symbol  $x_i$  is  $P_X(x_i)$ ,  $i = 1, 2, \dots, N$  and the channel output signal is  $Y = y_1, y_2, \dots, y_M$ ,  $j = 1, 2, \dots, M$ . The channel transition probability matrix is denoted as  $P = P(y_j|x_i)$ , that is, the probability of receiving  $y_j$  under the condition of transmitting  $x_i$ . Define the maximum mutual information of the input and output as the channel capacity:

$$C = \max_{P_X} I(X; Y) = \max_{P_X} \sum_i P_X(x_i) \sum_j P(y_j|x_i) \log_2 \frac{P(y_j|x_i)}{P_Y(y_j; P_X)} \quad (2)$$

where  $P_Y(y_j; P_X)$  represents the probability mass function of the channel output signal  $Y$ . The input signal and output signal of the continuous channel are continuous time functions, and its channel capacity can be expressed as

$$C = \sup_{F_X} I(X; Y) = \sup_{F_X} \int \int P(y|x) \log_2 \frac{P(y|x)}{P_Y(y; F_X)} dy dF_X(x) \quad (3)$$

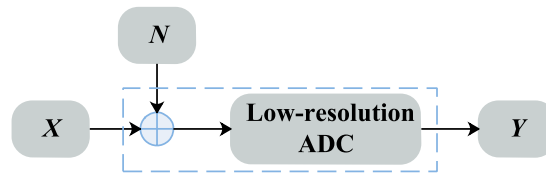


FIGURE 5. Quantized output channel of AWGN.

where  $P(y|x)$  represents the transition probability density function of the channel,  $F_x$  is the cumulative distribution function of the input signal, and  $P_Y(y; F_x)$  is the probability density function of the output signal in the case of channel input  $X$ .

We consider linear modulation over a real AWGN channel, with symbol rate Nyquist samples quantized by a  $K$ -bin quantizer at the receiver. This induces the following discrete-time memoryless AWGN quantized output channel whose model is shown in Figure 5.

The quantized output channel can be expressed as

$$Y = Q(X + N) \quad (4)$$

where  $X \in \mathbb{R}$  is the channel input with cumulative distribution function  $F(x)$ ,  $Y \in \{y_1, y_2, \dots, y_k\}$  is the discrete channel output,  $Q(\cdot)$  is the quantization function,  $N$  is a Gaussian random variable with zero mean and  $\sigma^2$  variance. The quantizer with  $K$  bins is therefore characterized by the set of its  $K - 1$  thresholds  $q := [q_1, q_2, \dots, q_{k-1}] \in \mathbb{R}^{K-1}$ , such that  $-\infty := q_0 < q_1 < \dots < q_{k-1} < q_k := \infty$ . The output  $Y$  is assigned the value  $y_i$  when the quantizer input  $X + N$  falls in the  $i^{th}$  bin, which is given by the interval  $(q_{i-1}, q_i]$ . The resulting transition probability functions can be expressed as

$$W_i(x) = P(Y = y_i | X = x) = Q\left(\frac{q_{i-1} - x}{\sigma}\right) - Q\left(\frac{q_i - x}{\sigma}\right) \quad (5)$$

where  $1 \leq i \leq K$ ,  $Q(\cdot)$  represents complementary Gaussian distribution function.

$$Q(\varphi) = \frac{1}{\sqrt{2\pi}} \int_{\varphi}^{\infty} \exp(-t^2/2) dt \quad (6)$$

The probability mass function of the output  $Y$ , corresponding to the input distribution of  $F$  can be expressed as

$$R(y_i; F) = \int_{-\infty}^{\infty} W_i(x) dF(x) \quad (7)$$

The mutual information of input and output can be expressed as [14].

$$I(F) = \int_{-\infty}^{\infty} \sum_{i=1}^K W_i(x) \log_2 \frac{W_i(x)}{R(y_i; F)} dF(x) \quad (8)$$

Because of the serious nonlinearity between the input and output of ADC, it is quite complicated to analyze parameters directly by quantization intervals and quantization reconstruction points in wireless communication system. Many results have no explicit solution, only numerical solution. Some existing researches on ADC mainly focuses on the

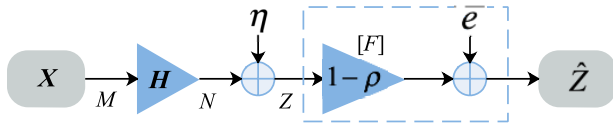


FIGURE 6. Quantized output channel of AQNM.

use of uniform quantization, which greatly simplifies the difficulty of analysis. However, the uniform quantization is suboptimal compared with the non-uniform quantization, and the performance difference between them may be obvious. Therefore, the practical significance of the uniform quantization method is not so prominent.

2) ADDITIVE QUANTIZATION NOISE OUTPUT CHANNEL MODEL

Unlike the AWGN output channel model, in AQNM, the output signal of the quantizer is represented as the sum of a scaled input signal and a quantization noise uncorrelated with the input signal by Bussgang decomposition [15]. Therefore, AQNM shields the internal characteristics of the ADC and enables the conversion of the channel output model from nonlinear modeling to linear modeling.

Specifically, for a general system model of a MIMO channel with  $M$  transmit antennas and  $N$  receive antennas shown in Figure. 6 and described by

$$\hat{Z} = FZ + e \tag{9}$$

$$Z = Hx + \eta \tag{10}$$

where  $Z$  is the zero-mean unquantized receive vector,  $e$  is the additive quantization noise independent of the input signal  $x$ , and  $F$  is taken as the minimum mean square error (MMSE) estimator of  $\hat{Z}$  from  $Z$ .  $\eta$  is a Gaussian noise with covariance matrix  $R_{\eta\eta}$ .  $H \in \mathbb{C}^{N \times M}$  is the channel matrix and  $x$  is the unknown data vector.

$$F = E(\hat{Z}Z^H)E(ZZ^H)^{-1} \tag{11}$$

and the distortion error  $e$  has the following correlation matrix

$$\begin{aligned} R_{ee} &= E\{(\hat{Z} - FZ)(\hat{Z} - FZ)^H\} \\ &= R_{\hat{Z}\hat{Z}} - R_{\hat{Z}Z}R_{ZZ}^{-1}R_{ZZ}^H \end{aligned} \tag{12}$$

Based on this decomposition, the channel output  $\hat{Z}$  can be written as function of the channel input in the following form

$$\begin{aligned} \hat{Z} &= FZ + e \\ &= FHx + F\eta + e \\ &= H'x + \eta' \end{aligned} \tag{13}$$

where we introduced the effective channel

$$H' = FH = R_{\hat{Z}Z}R_{ZZ}^{-1}H \tag{14}$$

and the non-Gaussian effective noise  $\eta'$  with the covariance matrix

$$\begin{aligned} R_{\eta'\eta'} &= R_{ee} + FR_{\eta\eta}F^H \\ &= R_{\hat{Z}\hat{Z}} - R_{\hat{Z}Z}R_{ZZ}^{-1}R_{ZZ}^H \\ &\quad + R_{\hat{Z}Z}R_{ZZ}^{-1}R_{\eta\eta}R_{ZZ}^{-1}R_{ZZ}^H \end{aligned} \tag{15}$$

Next, we introduced the MIMO Gaussian channel that is described by the same effective channel matrix  $H'$  and the same effective noise covariance matrix

$$\hat{Z}_G = H'x + \eta_G \tag{16}$$

but differs from the original channel by the fact, that the noise vector  $\eta_G$  is Gaussian distributed with the same covariance matrix  $R_{\eta'\eta'} = E(\eta_G\eta_G^H)$ . In [16], it was shown that, for a given noise covariance matrix (known at the receiver), the Gaussian distributed noise minimizes the mutual information, which leads to the following lower bound.

$$I(x; \hat{Z}) \geq I(x; \hat{Z}_G) \tag{17}$$

where  $I(x; \hat{Z}_G)$  corresponds to the mutual information of the MIMO Gaussian channel, that reads as

$$I(x; \hat{Z}_G) = \log_2 |I_N + R_{\eta'\eta'}H'R_{xx}H'^H| \tag{18}$$

where  $I_N$  denotes the identity matrix. when the channel input  $x$  is Gaussian distributed with the covariance matrix  $R_{xx}$ . Again,  $H'$  and  $R_{\eta'\eta'}$  are given in (14) and (15) respectively. The main difficulty consists of deriving the covariance matrices  $R_{\hat{Z}\hat{Z}}$  and  $R_{\hat{Z}Z}$  assuming a Gaussian input  $x$ . For general scalar quantizers, an approximate evaluation can be described as follows.

Each quantization process can be given a distortion factor  $\rho_q^i$  to indicate the relative amount of quantization noise generated, and the SQNR has an inverse relationship with regard to the distortion factor. The  $\rho_q^i$  of the  $i$ th group quantizer is defined as follows

$$\rho_q^i = \frac{E(q_i^2)}{r_{z_i z_i}} = \frac{1}{\text{SQNR}_i} \tag{19}$$

where  $q_i = \hat{z}_i - z_i$  and  $r_{z_i z_i} = E(z_i^2)$ .  $q_i$ ,  $z_i$ , and  $\hat{z}_i$  denote the  $i$ th elements of the corresponding set respectively. For a symmetric input probability density function and a symmetric quantizer, we can assume without loss of generality that the following properties holds for all  $0 \leq i \leq N$ :  $E(q_i) = 0$ ,  $E(\hat{z}_i q_i) = 0$  and  $E(z_i q_i) = -\rho_q^i r_{z_i z_i}$ . Assuming that the channel input is Gaussian then the quantizer input signals  $z_i$  are Gaussian distributed and thus, they undergo the same distortion factor  $\rho_q^i$ , i.e.,  $\rho_q^i = \rho_q$ ,  $i = 1, 2, \dots, N$ . Now, let  $q_i = \Re(q_i) + j\Im(q_i)$  be the complex quantization error where  $\Re(q_i)$  and  $\Im(q_i)$  are the real part and imaginary part of  $q_i$ , respectively. Under the assumption of uncorrelated real and imaginary part of  $z_i$ , we obtain:

$$r_{q_i q_i} = E(q_i q_i^*) = \rho_q r_{z_i z_i} \tag{20}$$

$$r_{z_i q_i} = E(z_i q_i^*) = -\rho_q r_{z_i z_i} \tag{21}$$

For the uniform quantizer case, it was shown in [17], that the optimal quantization step  $\Delta$  for a Gaussian source decreases as  $\sqrt{b} \cdot 2^{-b}$  and that  $\rho_q$  is asymptotically well approximated by  $\Delta^2/12$  and decreases as  $b \cdot 2^{-2b}$ . On the other hand, the optimal non-uniform quantizer achieves, under high resolution assumption, approximately the distortion  $\rho \approx \pi\sqrt{3} \cdot 2^{-2b-1}$  [16]. Based on these considerations,

we aim at approximating the required correlation matrices  $R_{\hat{Z}\hat{Z}}$  and  $R_{\hat{Z}\hat{Z}}$  based on the scalar  $\rho_q$ . In fact, we have

$$R_{\hat{Z}\hat{Z}} = E\{Z(Z + q)^H\} \quad (22)$$

and  $R_{\hat{Z}\hat{Z}}$  can be expressed as

$$\begin{aligned} R_{\hat{Z}\hat{Z}} &= (Z + q)(Z + q)^H \\ &= R_{ZZ} + R_{Zq} + R_{Zq}^H + R_{qq} \end{aligned} \quad (23)$$

Next, we need to derive all required covariance matrices by using the fact that the quantization error  $q_i$ , conditioned on  $y_i$ , is statistically independent of all other random variables of the system. For  $i \neq j$ ,  $r_{z_i q_j} = E(z_i q_j^*)$ :

$$\begin{aligned} E(z_i q_j^*) &= E_{z_j}\{E(z_i q_j^* | z_j)\} \\ &= E_{z_j}\{r_{z_i z_j} r_{z_j z_j}^{-1} z_j E(q_j^* | z_j)\} = -\rho_q r_{z_i z_j} \end{aligned} \quad (24)$$

In (24), the Bayesian estimator  $E(z_i | z_j)$  corresponds to the linear estimator  $r_{z_i z_j} r_{z_j z_j}^{-1} z_j$  since the vector  $Z$  is jointly Gaussian distributed. Summarizing the results of (21) and (24), we obtain  $R_{Zq} = -\rho_q R_{ZZ}$ , and the  $R_{\hat{Z}\hat{Z}}$  can be expressed as

$$R_{\hat{Z}\hat{Z}} = R_{ZZ} + R_{Zq} = (1 - \rho_q)R_{ZZ} = R_{\hat{Z}\hat{Z}} \quad (25)$$

Combine the results of (25) with (11) to get

$$F = (1 - \rho_q)I_N \quad (26)$$

In a similar way, we evaluate  $r_{q_i q_j}$  for  $i \neq j$ :

$$\begin{aligned} E(q_i q_j^*) &= E_{z_j}\{E(q_i q_j^* | z_j)\} \\ &\approx E_{z_j}\{r_{q_i z_j} r_{z_j z_j}^{-1} z_j E(q_j^* | z_j)\} = \rho_q^2 r_{z_i z_j} \end{aligned} \quad (27)$$

From (27) and (20), we deduce the covariance matrix of the quantization error:

$$R_{qq} = \rho_q R_{ZZ} + (1 - \rho_q)\rho_q(R_{ZZ} - \text{diag}(R_{ZZ})) \quad (28)$$

Summarizing the results of (20), (21), (24) and (28), the covariance matrix of  $e$  can be approximated as

$$R_{ee} = (1 - \rho_q)\rho_q \text{diag}(R_{\hat{Z}\hat{Z}}) \quad (29)$$

Inserting the expressions (25) and (28) into (22), we obtain:

$$R_{\hat{Z}\hat{Z}} = (1 - \rho_q)((1 - \rho_q)R_{ZZ} + \rho_q \text{diag}(R_{ZZ})) \quad (30)$$

While the effective noise covariance matrix from (15) can be obtained by means of (25) and (28)

$$R_{\eta'\eta'} = (1 - \rho_q)((1 - \rho_q)R_{\eta\eta} + \rho_q \text{diag}(R_{ZZ})) \quad (31)$$

Finally, we obtain the approximate lower bound on the mutual information as

$$\begin{aligned} I(x; \hat{Z}_G) &\approx \log_2 |\mathbf{I}_N + (1 - \rho_q)((1 - \rho_q)R_{\eta\eta} \\ &\quad + \rho_q \text{diag}(R_{ZZ}))^{-1} H R_{xx} H^H| \end{aligned} \quad (32)$$

where  $R_{ZZ} = R_{\eta\eta} + H R_{xx} H^H$ .

The AQNM constructs the digital output as the sum of the analog input and a random noise compared to the physical ADC characterized by the quantization interval and the quantized reconstruction point, approximating a complex nonlinear process to a simple linear process. Therefore, AQNM can be applied to various scenarios for analysis to reduce computational complexity.

### C. PERFORMANCE ANALYSIS OF LOW-RESOLUTION QUANTIZATION SYSTEM

#### 1) PERFORMANCE ANALYSIS OF LOW-RESOLUTION QUANTIZATION SYSTEM BASED ON AWGN QUANTIZED OUTPUT CHANNEL MODEL

Reducing the resolution of the ADCs must have an impact on the performance of the communication. The most extreme scenario is that the receiver uses one-bit ADC at the baseband. This effect will be constrained to various aspects of system design, such as channel capacity, synchronization, and channel estimation.

The optimal distribution of input signals at low resolution over real-valued additive Gaussian channels is discussed in detail in [9], [18], [19]. Dabeer *et al.* (2006) [18] analyzed Shannon's theoretical limits on the ideal discrete-time real-baseband AWGN channel under one-bit. The results showed that binary phase shift keying (BPSK) is optimal in non-spread spectrum systems, but for spread spectrum systems, the sub-optimality of BPSK and non-monotonicity of mutual information with signal-to-noise ratio (SNR) for a fixed constellation is not ideal. Further promotion as [18], Singh *et al.* (2008) [19] used a dual formulation to compute the capacity, which is attractive due to the discrete nature of the output alphabet. The numerical results showed that the optimal input distribution is discrete, and has at most one mass point in each quantizer interval. In the same year, Singh *et al.* [9] showed that for any given output quantizer choice with  $K$  quantization bins, the input distribution, under an average power constraint, need not have any more than  $K + 1$  mass points to achieve the channel capacity. For multi-bit quantization, Singh *et al.* (2009) [19] used the cutting-plane algorithm to compute the capacity numerically. They inferred that the use of low-resolution ADCs incurs a relatively small loss (2-3 bit quantization results in only 10%-20% reduction when SNR up to 20dB) in spectral efficiency compared to unquantized observations. Furthermore, they observed that equiprobable pulse amplitude modulated (PAM) input with ADC thresholds set to implement maximum likelihood (ML) hard decisions can achieves performance which is quite close to that obtained by numerical optimization of the quantizer and input distribution.

In addition to the above references studying the additive Gaussian channel capacity at low resolution, the academic community has also begun a series of studies on the impact of low-resolution quantification in different systems. In the context of UWB communications, Mezghani *et al.* (2007) [20] considered the extreme case of only 1-bit ADC for each receive signal component. They showed that, up to first order in SNR, the mutual information of the 1-bit quantized system degrades only by a factor of  $2/\pi$  compared to the system with infinite resolution independent of the actual MIMO channel realization. For the mutual information of the Rayleigh-fading MIMO channels with one-bit ADC, Mezghani *et al.* (2008) [21] indicated that the non-coherent single input single output (SISO) capacity can be achieved by on-off quadrature phase shift keying (QPSK) for the whole

SNR range, where the optimal duty cycle depends only on the coherence time. Assuming channel state information (CSI) is known at the receiver, Krone et al. (2010) [22] investigated optimal modulation schemes, the ergodic capacity and the outage probability for complex-valued fading channels with 1-bit output quantization. They found that a necessary constraint on the optimal input distribution to maximize the achievable rate of such channels is circular symmetry with at most one amplitude per phase. And the ergodic capacity of Rayleigh-fading channels with 1-bit output quantization and channel knowledge at the receiver can be achieved with  $L$ -PSK, where  $L$  is a multiple of 4. For oversampled AWGN channel with 1-bit quantization, Koch et al. (2010) [23] demonstrated that doubling the sampling rate recovers some of the loss in capacity per unit-cost incurred on the bandlimited Gaussian channel with a one-bit output quantizer. However, the results of this analysis are limited to have a very low SNR. For not limited to high or low SNR, Krone et al. (2012) [24] analyzed the channel capacity with 1-bit quantization and oversampling at the receiver for the particular case of AWGN channels. The analysis illustrated that oversampling can increase the channel capacity to much more than 2bpcu.

In [25] and [26], Mo et al. (2014&2015) analyzed the flat fading MIMO channel with one-bit ADC. They developed accurate bounds on the infinite SNR capacity by relating it to a problem in classical combinatorial geometry. And they proposed a computationally efficient method based on convex optimization to design the input alphabet such that the infinite SNR capacity is approached. Jacobsson et al. (2017) [27] investigated the quantized uplink massive multiuser MIMO (MU-MIMO) system over a frequency at Rayleigh block-fading channel. They found that for the 1-bit massive MIMO case, high-order constellations, such as 16- quadrature amplitude modulation (QAM), can be used to convey information at higher rates than with QPSK. In [28], Roth et al. (2017) further extended the capacity analysis to mmWave systems. In their work, they conducted a comparative performance analysis regarding the uplink achievable rate region for low-resolution ADCs digital beamforming and hybrid beamforming in a massive MIMO scenario. The results indicated that in the low SNR regime, the low-resolution ADCs digital beamforming is clearly superior compared to hybrid beamforming. Different from the above research work, Rini et al. (2017) [29] were devoted to examining the capacity of a discrete-time MIMO Gaussian channel with output quantization for different analog receiver architectures. In their work, three analog receiver architectures are considered: (i) multiple antenna selection and sign quantization, (ii) Single antenna selection and multilevel quantization, (iii) linear combining of the antenna outputs and multilevel quantization. Then, they proposed a unified framework where the each sign quantizer is connected to the antenna outputs to model the receiver architectures for multi-antenna channels with low-resolution output quantization. Through this framework, it is possible to optimize the capacity expression over

the set of feasible analog processing operations while keeping the number of sign quantizers fixed. Based on the three models proposed in [29], Khalili et al. (2018) [30] explored the capacity of a MIMO channel in which the antenna outputs are processed by an analog linear combining network and quantized by a set of threshold quantizers. The linear combining weights and quantization thresholds are selected from a set of possible configurations as a function of the channel matrix. Analysis showed that for a given number of quantizers, choosing configurations which induce a larger number of partitions can lead to higher rates. In [31], Dong et al. (2018) further concentrated on the impact of the spatial correlation on the rate loss caused by low-resolution ADCs. They found that low-resolution ADCs can achieve the sum rate much closer to the ideal ADCs case under spatially correlated channels. It is good news since channel correlation always exists in the practical massive MIMO implementation.

## 2) PERFORMANCE ANALYSIS OF LOW-RESOLUTION QUANTIZATION SYSTEM USING AQNM

Although many literatures provide closed-form expressions for optimal input and capacity under a 1-bit quantizer, it is difficult to obtain the capacity and input distribution of a multi-bit quantizer. Therefore, we limit the analysis to AQNM, under which the ADC power constraints can be easily abstracted into constraints on sample rate and quantizer noise levels. Then we can get the lower bound of the capacity and study the optimal bandwidth and ADC resolutions to maximize the rate. As the resolution of the ADC improves, the quantization error is reduced, and the communication rate is increased, but the ADC consumes more power, which increases the total energy consumption of the receiver. The trade-off between communication rate and ADC resolutions is especially important for energy efficient designs of receivers with multiple antennas.

In [32], Bai et al. (2013) studied the joint optimization problem of the number of system antennas and ADC resolutions under ideal CSI based on AQNM. The author used particle swarm optimization algorithm to achieve approximate optimality under low complexity solution. The simulation results showed that the energy efficiency is improved compared to the general design using a uniform ADC resolution, thus demonstrating the necessity of implementing such an optimization scheme. Orhan et al. (2015) [33] investigated the effect of ADC resolutions and bandwidth on the achievable rate for a multi-antenna system under a receiver power constraint. The results showed that when only ADC power budget is constrained, operating regime analog combining may have higher rate but digital combining utilizes less bandwidth. However, when power consumption of all the receiver components are taken into account, the digital combining may have higher rate, and in some cases, it can be optimal to increase the number of antennas or the increase the resolution while reducing the bandwidth. Compared with the [33], Mo et al. (2017) [34] studied the generalized hybrid



architectures with few-bit ADC in mmWave systems. The channel inversion method and singular value decomposition (SVD) method are used to derive the channel capacity. The lower bound of the achievable rate is obtained by assuming a Gaussian input distribution. They revealed that the generalized hybrid architecture with few-bit ADCs can achieve a performance comparable to that obtained with fully-digital or hybrid architecture with infinite-bit ADC receiver in the low-to-medium SNR range. It is worth mentioning that their work can achieve the best trade-off between achievable rate and power consumption.

To discuss the feasibility and economic applicability of low-resolution ADCs in massive MIMO systems, the following references have already done relevant work. Under the assumption of perfect CSI at base station (BS), Fan et al. (2015) [35] investigated the uplink achievable rate of a massive MIMO antenna system when finite-resolution ADCs and the common maximal-ratio combining (MRC) technique are used at the receivers. The results proved that the performance loss caused by low-resolution ADCs can be compensated by increasing the number of BS antennas, which implies the feasibility of installing low-resolution ADCs in massive MIMO systems. On the basis of the [35], Zhang et al. (2015) [36] studied the uplink spectral efficiency of massive MIMO systems with low-resolution ADCs over Rician fading channels. They came up with an interesting finding that there appears a fixed constant loss of spectral efficiency related to the ADC quantization bit, which is quite different from unquantized massive MIMO systems. Moreover, the Rician  $K$ -factor has a noticeable reduction effect on the spectral efficiency of massive MIMO systems with low-resolution ADCs. Different from the work done in [35] and [36], most of their work assumes that the perfect CSI is known in the BS, which is not well justified in practical systems. Liu et al. (2018) [37] investigated the uplink achievable rate with only imperfect CSI is known at the BS. They found that the performance loss due to the low-resolution quantization is not as severe as might be imagined and only 1.1 times more antennas are needed to be installed at the BS to compensate the performance loss for 2-bit quantization systems. In addition to the pure low-resolution ADC architecture described above, we have recently noticed that AQNM is also used for performance analysis in a mixed-ADC architecture. The relevant content of the mixed-ADC architecture will be explained in the next subsection.

#### **D. GENERAL APPROACHES TO SYSTEM PERFORMANCE IMPROVEMENT**

In the previous section, we introduced some work related to the impact of low-resolution quantization on system performance. As indicated by extensive research results, low-resolution ADCs have favorable properties such as reduced circuit complexity, low power consumption, and feasible implementability. However, these converters inevitably deteriorate performance and complicate receiver design. In this section, we will review some implementations that

are beneficial to system performance improvement from the perspective of receiver architecture.

In [38], Liang et al. (2016) developed a mixed-ADC architecture, in which some antennas are equipped with costly full-resolution ADCs and others with less expensive low-resolution ADCs. In their work, they revealed that the mixed-ADC architecture with a small proportion of high-resolution ADCs is able to achieve a large fraction of the channel capacity of ideal-ADC architectures over frequency-flat channels, and that it remarkably improves the performance as compared with one-bit massive MIMO. Tan et al. (2016) [39] utilized the AQNM to derive a closed-form approximation of the achievable rate of the mixed-ADC architecture. Benefiting from the receiver equipped with full-resolution ADCs, the data with negligible quantization errors can be used for time-frequency synchronization and channel estimation, resulting in a significant reduction in overhead. Their observations indicated that the mixed-ADC structure can have comparable spectral efficiency performance with the receiver with all full-resolution ADCs. Moreover, this architecture can bring most of the desired performance enjoyed by massive MIMO receivers with full-resolution ADCs, and with significantly reduced hardware cost. The common assumption of the aforementioned works is that massive MIMO systems are operating over Rayleigh fading channels. Considering that Rician fading is more general and realistic than Rayleigh fading, Zhang et al. (2017) [40] investigated the performance of mixed-ADC massive MIMO systems over Rician fading channels. They first derived the closed-form of achievable rate and the power-scaling law for the mixed-ADC architecture. Then, the trade-off between the achievable rate and energy efficiency for different number of high-resolution ADCs and quantization bits is quantified by a generic power consumption model. The results demonstrated that practical massive MIMO can achieve a considerable performance with small power consumption by adopting the mixed-ADC architecture.

However, the work in [38], [40] forces antennas to select between 1-bit ADC and  $\infty$ -bit ADC, which is far from an energy-efficient architecture mainly because the total ADC power consumption can be dominated by only a few high-resolution ADCs. Moreover, it assumes full number of RF chains, which leads to dissipation of energy. To overcome these limitations, the bit allocation algorithm (BA) has received wide attention because of its ability to make the mixed-ADC architecture more flexible. Choi et al. (2017) [41] proposed a near optimal low-complexity BA algorithm. Having the total ADC power consumption of the receiver with uniform bit ADC as a power constraint, they formulated a relaxed mean square quantization error minimization problem for the beamspace signals under the AQNM assumption. The proposed method gives better communication performance than conventional low-resolution ADCs for the same or less power. In [42], Ahmed et al. (2017) put forward a genetic algorithm in conjunction with the derived

combiner. In their work, they first designed the combiner as a function of quantization error based on the MMSE criterion, and then used genetic algorithms to minimize MMSE to achieve optimal bit allocation. The proposed method arrived at an optimal ADC bit allocation framework with significant reduction in computational complexity. An ADC bit allocation algorithm based on channel SVD computation for single-user mmWave MIMO systems was introduced in [43]. This method minimizes the CRLB with respect to the bit allocation matrix by making suitable assumptions regarding the structure of the combiners. The computational complexity of the proposed method is an order of magnitude improvement over the method in [42]. In addition, Ahmed et al. (2018) [44] also presented a BA algorithm for a given power budget. This method maximizes the expression of the capacity derived by a given channel and hybrid combiner to arrive at a condition for optimal bit allocation. The capacity evaluated at various SNRs using the proposed BA method is very close to the exhaustive search technique. Different from their previous work [42]–[44], Ahmed et al. (2019) [45] designed a new BA scheme based on the mean squared error minimization criterion and capacity maximization criterion. In their method, they established a connection between mean squared error and capacity through CRLB and maximize capacity while minimizing mean squared error. Simulation results showed that the mean squared error and capacity performance of the proposed method is very close to that of the exhaustive search BA method. Moreover, the computational complexity of the proposed method has significant improvement compared to exhaustive search BA method.

### E. SUMMARY AND OPEN ISSUES

From the current research work, the analysis of capacity under low precision is mainly based on AWGN and AQNM output channels. Under the AWGN model, it is divided into real-valued channels and complex-valued channels. In the context of low-resolution quantization, the previous work has made comprehensive research on the optimal input distribution of real-valued channels and the channel performance of complex-valued channels at low, medium and high SNR. The main focus of these efforts is the performance loss caused by low-resolution quantification and how to compensate for this loss by some means. It is now less inclined to solve for maximum channel capacity under fixed local constraints. On the contrary, the current research trend is more concerned with the change of channel capacity from the overall model of the low-resolution quantization system. By considering the optimal hybrid analog/digital architectures, the maximum achievable rate can be realized. For the solution of capacity under low resolution, it is mainly concentrated in the case of single bit. Due to the nonlinearity of the AWGN model, the modeling and analysis of system capacity under multi-bit quantization is very difficult. The theory involved in multi-bit quantization is much more complicated than in the single bit scenario, and the multi-bit quantization theory has not yet been perfected. As far as the current situation is

concerned, the theoretical improvement of the receiver for multi-bit is still very difficult. There is still a problem that the existing research work is unbalanced between the uplink and the downlink. The results of many references are only for the uplink with coarse quantification, and the discussion on the downlink is very scarce.

For the AQNM, it overcomes the nonlinearity of the AWGN model, allowing researchers to take a step forward in analyzing various performance indicators for low-resolution quantification systems. It is easy to utilize AQNM to solve some problems which are difficult to deduce in AWGN model. At present, the research trend of AQNM is similar to that of AWGN model and the models are more concerned with the generalized hybrid analog/digital architectures than to a narrow one. Since the power constraint is mainly considered under the AQNM, in the previous research work, more attention was paid to the spectral efficiency and energy efficiency of the system. According to the latest research based on AQNM, the BA solutions in the mmWave system have received extensive attention from researchers. The BA method can effectively overcome the drawbacks of the mixed-ADC architecture, enabling the antennas to select the ADCs with the optimal resolution to achieve a significant increase in system performance. Equally important is that the optimal signaling alphabet distribution for mmWave channels under low-resolution quantization. Since the wavelength of mmWave carriers is very short compared to the typical size of objects in the propagation environment, the performance investigation of massive MIMO systems with ADC quantizers should consider the unique channel characteristics of mmWave scenarios. Furthermore, because the AQNM overcomes the nonlinearity of quantization, the research work under the AQNM can better advance to the multi-bit scenario to analyze system performance. This advantage is not available in the AWGN model. Of course, from a practical point of view, the AWGN model is more closely related to the channel situation in the real system, which embodies the essential properties of the channel.

### III. SOME KEY TECHNOLOGIES RELATED TO LOW-RESOLUTION ADCs

The research and application of receivers with low-resolution ADCs first appeared in UWB communication systems. Recently, the academic community has extended its research scope to large-scale MIMO systems and mmWave systems. The receiving technology with low-resolution quantization is mainly concerned with the feasibility structure design of the receiver to guide the implementation of the low-resolution quantization system in practice. Although receivers with low-resolution quantization have made some progress, some key issues such as timing synchronization and carrier synchronization under low-resolution quantization have not been effectively solved. Recent research results on low-resolution quantization systems not only provide performance indicators for low-resolution ADCs receiver technology, but also greatly facilitate the research process of receiver technology under

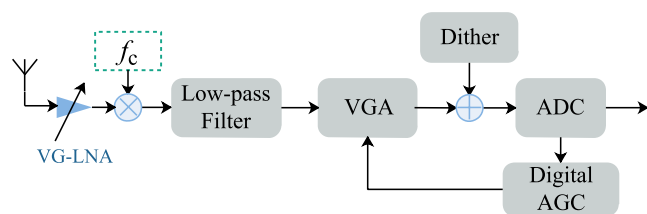


FIGURE 7. The architecture of low-resolution quantization digital receiver.

low-resolution quantization. It is foreseeable that under the promotion of 5G, receiver technology with low-resolution ADCs will become the focus of future research in the field of communication.

In this section, we mainly discuss several key issues and development status of receiver technology under low-resolution quantization. The detailed contents are scheduled as follows. In subsection A, the technical classification and research progress of AGC are introduced. Then the timing synchronization and carrier synchronization are discussed in detail in subsection B. The research progress and challenges of channel estimation are illustrated in subsection C. Finally, the data detection and receiver design with low-resolution ADCs are described in subsection D.

#### A. AUTOMATIC GAIN CONTROL

The wireless communications field is increasingly looking to move more signal processing from analog to digital to increase reliability and flexibility while reducing device size, power consumption, and cost. It is common practice to analog-to-digital convert a signal from RF to intermediate frequency (IF, 455KHz to 255MHz) for the first time and digitally process it at the IF or subsequent baseband. With the advent of high-speed and high-resolution ADCs, digital processing on this IF has also become possible. However, this development puts a lot of pressure on the ADCs. It must be ensured that the ADC has sufficient dynamic range and resolution to handle the drastically changing signal without excessive SNR or even system malfunction. In engineering, as an effective technique to improve the dynamic range, the main function of the AGC is to keep the amplitude of the output signal substantially constant or to vary only within a small range [46]. Due to the effects of quantization noise, aperture jitter, differential nonlinear distortion, and thermal noise caused by the ADCs, the input dynamic range and effective output bits of ADC are decreased, which will limit the input dynamic range of intermediate-frequency signal. In order to improve the input dynamic range of the ADC, AGC assistance is required.

AGC can be divided into RF analog control and ADC front-end digital control [47]. The former works by extracting the analog signals received by the receiver as control parameters, while the latter extracts the digital signals from the back end of ADC as control parameters and obtains the actual control signals through certain algorithm processing. Considering the small dynamic range of the low-resolution ADCs, how

to effectively use all the quantization intervals and implement high-resolution digital AGC is the key problem to be solved in low-resolution quantization. At present, the research on low-resolution quantization signal processing technology usually assumes the ideal AGC. The research progress of AGC in low-resolution quantization system is still in its infancy. To achieve high performance with low-resolution ADCs, it requires the AGC optimally scales the signal to meet the quantizer boundaries. The classical method is to measure the energy or amplitude of the ADC output signals and average them over time. This method works well with sufficient resolution ADCs. However, the low-resolution ADCs introduce grievous quantization noise, which decreases the performance of the conventional energy measurement. A typical receiver front-end is shown in in Figure 7. It consists of a variable gain low-noise amplifier (VG-LNA) operating at RF, a down-conversion stage, and a variable gain amplifier with a digital AGC at the baseband. The power of the incoming RF signal can vary significantly due to path loss and fading. The VG-LNA adjusts its gain so to bring the power level within a smaller dynamic range, while the digital AGC sets the fine-grained scaling implemented using the variable gain amplifier at the ADC input. The addition of dither signals can further improve the performance of the system.

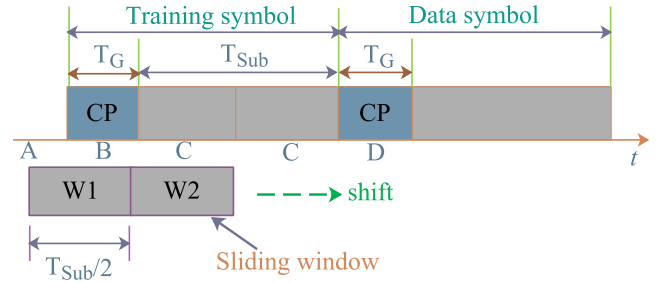
Murray et al. (2006) [48] analyzed the effects of AGC and quantization in a zero forcing (ZF) MIMO wireless system. They found that even quite low-resolution quantizers can perform close to the capacity of ideal unquantized systems. For BPSK and  $M$ -ary QAM, and for  $2 \times 2$ ,  $3 \times 3$ , and  $4 \times 4$  MIMO configurations, they also shown that in each case less than 6 quantizer bits are required to achieve 98% of unquantized capacity for SNRs above 15dB. The problem of AGC for PAM signaling over the AWGN channel was investigated in [49] (Sun et al., 2011). In their work, the gain is determined by estimating the signal amplitude from the quantized ADC output. Then, ML estimate for the signal amplitude is obtained based on the quantized samples corresponding to an unknown symbol sequence. Their approach obtained good performance, in terms of both channel capacity and uncoded bit error rate (BER), at low to moderate SNR. Interestingly, the performance actually degrade as SNR increases due to the increased sensitivity of the ML estimator in this regime. However, by introducing a random Gaussian dither signal, it is possible to improve the performance degradation at high SNR. Based on the work in [49], Sun et al. (2011) [50] further proposed an algorithm based on particle filter. With the help of particle filter algorithm, the quantization thresholds are adjusted according to the amplitude particles. Then, maximum a posteriori probability (MAP) estimate is made when the whole training sequence is received. Their work shown that without dither, the uncoded BER performance is still better than one-shot ML algorithm in [49]. In the same year, Sun (2011) put forward four kinds of amplitude estimation algorithms (ML algorithm, iterative maximal a posteriori probability algorithm, greedy estimation algorithm of optimal quantization threshold and particle filter based

estimation algorithm) for AGC of low-resolution quantization systems in her Ph.D. thesis [51]. However, these estimation algorithms do not consider synchronization problems, channel estimation problems, signal anti-interference and other issues under low-resolution quantization. For the fixed thresholds ADC, and altering the gain to ADC input, Ye et. al (2015) [52] presented an algorithm based on ADC output's distribution-function to adjust the gain of the amplifier in front of the ADC. In their work, the sequence used in the proposed algorithm can be training sequence or the transmitted data symbols. Different from the existing solutions [49], this method does not use the dither signal for SNR increasing to achieve acceptable estimation performance. Thus, the complexity of the receiver can be reduced. And the proposed AGC scheme in [52] can achieve a better estimation performance than that in [49].

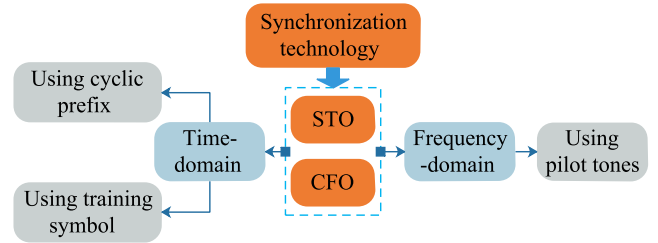
**B. SYNCHRONIZATION**

Synchronization is mainly divided into two parts: symbol time offset (STO) estimation and carrier frequency offset (CFO) estimation, in which carrier synchronization is studied the most. Carrier synchronization involves two steps of frequency acquisition and phase synchronization. In practical systems, frequency acquisition is performed first, leaving a signal constellation which is not rotating (or that rotates at a rate which is slow compared to the signaling rate) but has a constant phase offset that needs to be corrected by the phase synchronizer. The phase synchronization problem is invariably divided into an acquisition and a tracking part. In many practical systems, tracking is done simply and efficiently in a decision-directed mode [53], [54], and it is the acquisition problem that is more problematic, especially in applications where no preamble is allowed. The method of timing synchronization can be divided into two types: The first type of timing synchronization relies on redundant information in the received signal for estimation, which usually appears as a statistical characteristic of data in the guard interval. The second type inserts a pilot sequence (i.e., a PN sequence) in the transmission data according to a protocol agreed by the transmitting and receiving parties, and the receiving end performs timing synchronization on the symbol based on the received guiding sequence. Figure 8 illustrates the example of a single orthogonal frequency division multiplexing (OFDM) symbol with a repetitive structure of different repetition periods. Once the transmitter sends the repeated training signals over two blocks within the OFDM symbol, the receiver attempts to find the CFO by maximizing the similarity between these two blocks of samples received within two sliding windows. The similarity between two sample blocks can be computed by an auto-correlation property of the repeated training signal.

Modern communication transceiver designs leverage Moore's law for low-cost implementation (e.g., for today's cellular systems), by using digital signal processing (DSP) to perform sophisticated functionalities such as synchronization, equalization, demodulation, and decoding. The central assumption in such designs is that analog signals can be



**FIGURE 8.** A typical synchronization method based on training symbols.



**FIGURE 9.** The basic implementation of synchronization technology.

faithfully represented in the digital domain, typically using ADC with 8-12 bits of resolution. However, the key bottleneck to doing this is the ADCs, the cost and power consumption of high-resolution ADCs become prohibitive at multi-GHz sampling rates. Thus, it is natural to ask whether DSP-centric architectures with samples quantized at significantly low resolution can be effective. A receiver architecture was implemented for a gigabit/s 60 GHz system in [55], including blocks for both carrier synchronization and equalization. While the emphasis in [55] was on establishing the feasibility of integrated circuit implementation rather than algorithm design and performance evaluation, it makes a compelling case for low-power mixed signal designs at high data rates. Synchronization methods are mainly divided into time-domain based and frequency-domain based. The specific classification is shown in Figure 9. Some early related work on estimation using low resolution samples includes frequency estimation can be found in [56], [57], and the signal parameter estimation using 1-bit dithered quantization can be found in [58]. In addition, the effect of phase offset on the performance of low-resolution quantized receivers is reflected in [59].

The effect of using quantized phase on system performance is discussed in the following references. For standard uniform PSK modulation, Singh et al. (2009) [60] investigated the performance of a receiver architecture that quantizes only the phase of the received signal. In their work, they proposed to quantize the phase of the received signal using multiple 1-bit ADC. The phase quantization of 8-bin (equivalent to 2-bit) can achieve 80%-85% of full-resolution capacity, and is up to 90%-95% using 12-bin quantization (equivalent to 3-bit). The performance of the receiver can be further improved by adding phase jitter. However, their

method will also have a bad influence on the gain control, sampling timing and other parts of the system, which will increase the difficulty of parameter estimation. In 2013, Singh and Madhow [61] conceived a phase-quantized carrier-asynchronous system model which employed block non-coherent demodulation and approximated the phase as constant over a block of symbols. This approach incurred a loss of about 2dB with respect to unquantized block non-coherent demodulation. Fan et al. (2014) [62] focused on studying the performance of QPSK optical receiver with carrier phase estimation in the presence of finite-bit resolution ADCs and two carrier phase estimation schemes, decision-aided ML and  $M$ -th power, were considered. In their investigation work, the results shown that 5-bit ADC resolution is sufficient for both phase estimated schemes with less than 0.2dB SNR penalty compared with the case of infinite ADC resolutions.

To improve the synchronization performance under low-resolution quantization, researchers have proposed novel algorithms and useful insights to minimize the impact of quantization errors. Lin et al. (2011) [63] proposed a method to jointly estimate the CFO and the SISO channel using feedback dither control. In their work, they addressed the important problem at the front end of an OFDM system, i.e., CFO and channel estimation problem when using lower resolution ADCs. In [64] and [65], Wang et al. (2013) designed a single-bit quantization receiver with phase rotation assistance, and analyzed it from both theoretical and implementation perspectives. The results shown that, for QPSK signals, the quantization performance of the system can be maximally optimized when the auxiliary rotation is  $\pi/2$ . In order to obtain insight into the performance limitations imposed by severe quantization constraints, Wadhwa et al. (2013) [66] investigated a canonical problem of blind carrier phase and frequency synchronization. In their work, they used Bayesian algorithms for estimation and feedback generation. The architectures in [66] provided a promising approach for DSP-centric designs despite the ADC bottleneck encountered at high communication bandwidths. On the basis of [66], with the help of the random dither, Wadhwa et al. (2016) [67] implemented via a mixed signal architecture with a digitally controlled phase shift prior to the ADC, and then improved upon its performance with a simple feedback control policy that is close to optimal in terms of rapidly reducing the mean squared error of phase estimation. Performance evaluations for a QPSK system shown that excellent BER performance, close to that of an unquantized system, is achieved by the use of 8 phase bins. Li et al. (2016) [68] analyzed three CFO estimation algorithms for OFDM system with low-resolution quantization. Their results showed that the demodulation of a signal with CFO in the case of low-resolution quantization can cause a higher BER compared to full-resolution quantization, and that the optimal algorithm can effectively reduce the effect of low-resolution quantization. For OFDM-UWB system, Liu et al. (2018) [69] introduced a novel synchronization scheme which consists of two parts: one is the timing

estimator with one-bit ADC, and the other is the CFO estimator with multi-bit ADC. In their work, they verified the principle that the autocorrelation of the pseudo-noise (PN) sequences was not affected by low-resolution quantization. With the help of this property, the timing synchronization could be strongly implemented against the influence of low-resolution quantization. However, this method is designed for QPSK and its applicability to other modulation schemes is unknown. The recent related works on beamforming based directional synchronization design under low-resolution quantization are discussed in [70] and [71]. Zhu et al. (2017) [70] developed a new beamforming strategy for mmWave systems to improve the frame timing synchronization performance. In their work, they increased the received synchronization SQNR by optimizing the combination of the beam codewords in the beam cluster. However, this method is mainly used for performance improvement in a single user setup. To further advance the work [70] into multi-user scenario, Zhu et al. (2018) [71] proposed a new multi-beam probing based directional synchronization strategy. They formulated the corresponding directional frame timing synchronization problem as a max-min multicast beamforming problem. Then, a multi-beam probing based directional synchronization strategy was used to maximize the synchronization SQNR among all users. Numerical results revealed that the proposed method outperforms the existing approaches due to the improvement in the received synchronization SQNR.

### C. CHANNEL ESTIMATION

Channel estimation is crucial to support multi-user MIMO operation in massive MIMO systems. To reach the full potential of massive MIMO, accurate downlink CSI is required at the BS for precoding and other operations. Most literatures on massive MIMO systems assume a time division duplex (TDD) mode in which the downlink CSI can be immediately obtained from the uplink CSI by exploiting channel reciprocity [72]–[75]. Nevertheless, the channel estimation for massive MIMO systems with low-resolution ADCs is a challenging work since the magnitude and phase information about the received signal are lost or severely distorted due to the coarse quantization. Therefore, this means that the training sequence should be long enough to ensure a reliable CSI estimation. Figure 10 shows three types of pilot structure and some popular channel estimation algorithms for the readers to have a general understanding of channel estimation.

During 2001 and 2014, there has been some early related work on channel estimation with low-resolution ADCs and with one-bit ADC. A pilot-based channel estimation method using expectation-maximization (EM) algorithm was proposed and analyzed in [76], [77]. It was shown that in contrast to unquantized estimation, different orthogonal pilot sequences yield different performances. Especially, the orthogonality in the time-domain, i.e. time-multiplexed pilots, can be preferable to orthogonality in space. However, the problem solved in [76], [77] is not convex, and the EM

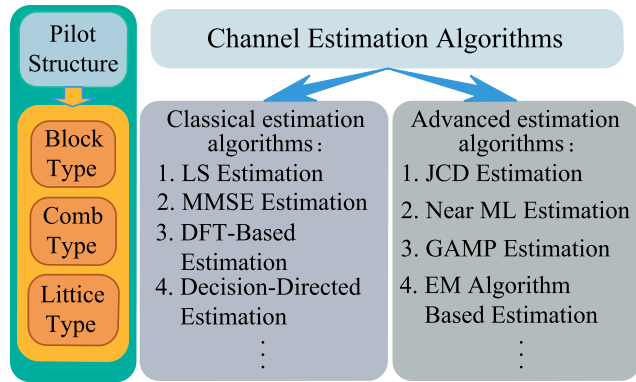


FIGURE 10. Some popular channel estimation algorithms.

algorithm may converge to a local optimal in the high SNR regime. A general EM-based approach for optimal parameter estimation based on quantized channel outputs was introduced in [78]. In their work, the authors found that the performance of proposed method is very close to infinite-resolution case when SNR at low regions. As the SNR increases, the performance gap gradually appears and is not monotonic. Unfortunately, this method only considers the 2-tap channel because the realistic wideband channels have many more taps. The channel estimation using comb-type pilots was considered in [79]. Although the estimation methods using comb-type pilots allow the channel to be treated as effectively flat-fading, these approaches perform poorly under peak-to-average power ratio limits. For the one-bit quantized ISI channel, a greed pursuit algorithm which combines an iterative method to estimate CSI was proposed in [80]. However, the proposed method has high complexity due to the use of an iterative algorithm. In [81] and [82], the authors used generalized approximate message passing (GAMP) algorithms for channel estimation with one-bit ADC, but the techniques heavily relied on the sparsity of the target vector. At the same time, it is worth noting that the computational complexities of the channel estimators introduced in [82] is expensive because it is based on the ML channel estimator. Regarding the nonlinear effects caused by coarse quantization, [83]–[85] illustrated that the introduction of dither signals can counter the nonlinear effects of low-resolution quantization.

The references presented above provide very useful insights for channel estimation under low-resolution quantization. For example, the channel estimation performance at low SNR seems to be independent of the quantizer, and the dither signals can be utilized to resist nonlinearities caused by coarse quantization. And the emerging new channel estimation methods are primarily a further extension of the above methods. For distributed reception scenarios, Choi et al. (2014) [86] proposed a practical channel estimation method for the block-fading scenario. This method relies on very simple operations at the received nodes while achieving near-optimal channel estimation performance as the training length becomes large. To avoid pilot contamination and to achieve better spectral efficiency, Masood et al. (2015) [87]

explored a novel channel estimation approach for estimating sparse channels. The proposed method utilizes the sparsity and common support properties to estimate sparse channels and only requires a small number of pilots. In contrast to [87], Stockle et al. (2016) [88] proposed a channel estimation method combining the EM algorithm with the sparse recovery algorithm. In this method, a priori knowledge of the sparsity in the time domain is used for channel estimation. In [89], Choi et al. (2016) further designed a near ML channel estimator for uplink MIMO systems. Their estimator is shown to estimate not only the channel direction but also the channel norm and does not make an assumption about sparsity in the channel. However, this estimator relies on either the ML algorithm or on an iterative algorithm with high complexity, and its performance is difficult to theoretically quantify. For one-bit massive MIMO systems, a long training sequence is still needed to obtain reliable CSI [90], [91]. To alleviate this issue, a Bayes-optimal joint channel and data estimation scheme was introduced in [92] (Wen et al., 2016), in which the estimated payload data are utilized to aid channel estimation. While the performance was comparable to the case with perfect CSI, the computational complexity of the joint technique may still be too high to be affordable in a commercial system.

More recently, Mollen et al. (2017) [93] concentrated on a low complexity channel estimator and the corresponding achievable rate for one-bit massive MIMO systems over frequency-selective channels. In their work, the number of channel taps goes to infinity, and the quantization noise is essentially modeled as independent, identically distributed noise. However, the generality of the model in [93] is inferior to that of the [94]. In [94], Li et al. (2017) propounded the Bussgang linear minimum mean squared error (LMMSE) channel estimator to mitigate the complexity of the ML estimator. This method uses the second-order channel statistics to formulate the one-bit LMMSE channel estimator based on the Bussgang decomposition. Regrettably, the estimator is only applicable to Gaussian distributed channels and OFDM systems. Cao et al. (2017) [95] developed a low complexity algorithm designed for low-resolution ADCs RF-frontend using iterative decoding based on approximate-message-passing. The proposed algorithm can provide adequate performance gains compared to approximate LMMSE solution. However, it does not leverage sparsity and requires OFDM. Compared with [95], the sparsity of the channel is utilized in the following work [96]–[99]. Zhou et al. (2017) [96] reported a practical channel estimation scheme for frequency division duplexing (FDD) massive MIMO systems. This scheme leverages the hidden joint sparsity structure in the user channel matrices to minimize the training and feedback overhead. Their method can achieve close-to-optimal performance with a small amount of training or feedback overhead. Considering that MIMO constant envelope modulation (CEM) can effectively overwhelm high power consumption in MIMO-OFDM transmitted signals, Shaimaa et al. (2017) [97] proposed a robust compressive sensing based

MIMO-CEM channel estimator. In their method, the channel estimate is divided into two phases. The sparsity property of the MIMO-CEM channel is first used to efficiently estimate a primary version of the MIMO-CEM channel. Then, the refinement adaptive filter utilizes the pre-estimated primary channel to estimate the accurate MIMO-CEM channel. Their approach not only reduces the channel estimation complexity, but also it introduces spectrum saving. Shaimaa et al. (2018) [98] further put forward a low complex and spectral efficient MIMO-CEM channel estimator. Similar to the method in [97], they used the adaptive compressive sensing recovery algorithm to replace inefficient high complex adaptive filter. And the sparsity nature of 1-bit ADC MIMO-CEM channel is utilized to estimate the channel. In [99] Sun et al. (2019) designed a fast and near-optimal channel estimation method over frequency-selective channels with few-bit ADC. In their work, they leverage parametric bilinear GAMP framework [100] and channel sparsity to reduce the complexity of the proposed method. In addition, some related early work of this approach was mentioned in [101]. All the previous work, however, has not considered the temporal correlation, which is inherent in all communication channels. Kim (2018) [102] developed a novel channel estimator which exploits both the spatial and temporal correlations of channels. In their approach, the Kalman filter is adopted to exploit the temporal correlation and perform successive channel estimation. The performance of proposed estimator has proven to have a substantial gain in low SNR regime.

The aforementioned related work is mainly for the general quantized MIMO channels, rather than the mmWave channels. In the context of mmWave communication, MIMO fully-digital architecture [103] and MIMO hybrid architecture [104]–[108] with low-resolution quantizers are attractive topics, because the combination of MIMO and beamforming can greatly extend the advantages of mmWave communication. In [103], Rusu et al. (2015) developed an adaptive one-bit compressed sensing scheme for narrowband mmWave MIMO channel estimation. This method can adaptively compute every new one-bit measurement without resorting to solving a full optimization problem during the adaptive process. It has been demonstrated that the adaptive scheme outperforms the fixed one for the application to channel estimation. In [104], Javier et al (2016) designed a compressive channel estimator. The proposed method exploits the sparse structure of the mmWave channel to compensate for the loss of information inherent to the mixed hybrid-low resolution MIMO architectures. The simulation results indicated that the proposed method can obtain acceptable performance even at low SNR. A broadband channel estimation algorithm for mmWave MIMO systems was introduced in [105] (Mo et al. 2018). This methodology exploits the joint sparsity of the mmWave MIMO channel in the angle and delay domains. In this method, the estimation problem is formulated as a noisy quantized compressed-sensing problem, and the approximate message passing algorithm is used to solve

it. Sung et al. (2018) [106] advocated a compressed sensing based channel estimation algorithm for narrowband mmWave channel. In their work, the variant of GAMP method is specifically designed for measurements taken with one-bit ADC. Moreover, the GAMP algorithm is modified to take the noise into account. Mezghani et al. (2018) [107] advocated a blind channel estimation method that relies on the EM algorithm. The proposed method significantly improves spectral efficiency by reducing pilot overhead and utilizing channel sparsity. Therefore, this method is robust to any type of statistical properties of the data and channels. In [108], Wang et al. (2018) designed a general hybrid estimator. The proposed channel estimator follows the typical LMMSE structure and can be applied to an arbitrary channel model. With the cooperation of orthogonal matching pursuit, the performance degradation caused by quantization noise to the estimator is greatly alleviated, so the proposed estimator is superior to the traditional estimator.

Quantization design is an interesting and important issue but largely neglected by existing massive MIMO channel estimation studies. In fact, most massive MIMO channel estimation schemes assume that the quantization threshold is fixed or typically zero [90]–[92], which is a convenient choice but could be far away from the optimum. Wang et al. (2018) [109] investigated the optimal design of quantization thresholds. They developed an adaptive quantization scheme which adaptively adjusts the thresholds, and a random quantization scheme which randomly generates a set of thresholds based on some statistical prior knowledge of the channel. The proposed quantization schemes achieved a significant performance improvement over the fixed quantization scheme. Moreover, these two schemes can help substantially reduce the training overhead while achieving considerable estimation accuracy. Stein et al. (2018) [110] concentrated on the problem of pilot-based channel parameter estimation from 1-bit quantized data with an unknown hard-limiting threshold. In their work, they considered a hybrid model [111]–[115] where the channel parameters are random and distributed according to a known probability distribution function, while the quantization offset is modeled as a deterministic unknown nuisance parameter. Then, the asymptotically optimal estimation algorithm is used to evaluate the performance of the models. They found that, under mild conditions on the channel model and the pilot signal, lack of offset knowledge does in general not degrade the performance in the low SNR regime. This means 1-bit ADC is an attractive design option for future low-complexity wireless systems, in particular when the receiver is intended to solve complex channel estimation tasks in the low SNR regime.

Considering the limited ability of existing channel estimation algorithms to resist synchronous impairments, some emerging joint CFO and channel estimation algorithms are used to solve this dilemma. In [116], Myers et al. (2017) reported a joint CFO and narrowband channel estimation algorithm. In their method, they used a third-order

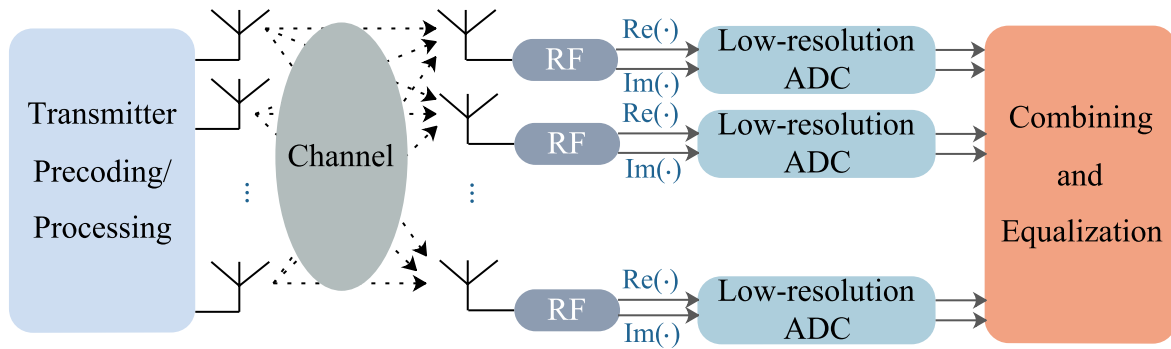


FIGURE 11. The structure of low-resolution quantized receiver.

tensors [117] to model the MIMO channel and CFO, and compressively estimated the tensor using the available measurements. Simulation results indicated that the proposed method performs better than algorithms that are robust to phase errors. As a further extension of [116], Myers et al. (2017) [118] put forward a compressive joint CFO and channel estimation algorithm using one-bit measurements. The key idea of their work is to jointly model the CFO-channel problem using lifting techniques [119]. Then, the expectation maximization generalized approximation message passing (EM-GAMP) is exploited to solve a noisy quantized compressed sensing problem and the SVD is used to recover the components corresponding to CFO. The results demonstrated that the proposed method is feasible to use one-bit measurements to recover both the channel and CFO. However, extending the narrowband solutions [116], [118] to typical wideband mmWave systems would require convex optimization over millions of variables, which may be prohibitive in a practical setting. In [120], Myers et al. (2018) further advocated a joint CFO and wideband channel estimation algorithm. In their work, they formulated the joint estimation as a sparse bilinear optimization problem and then used message passing for recovery. Unlike the existing methods that are specific to certain hardware architectures or that use non-coherent techniques, the proposed technique can be adapted to perform joint estimation with other mmWave architectures.

#### D. DATA DETECTION AND RECEIVER DESIGN

Most of the contributions on data detection and receiver design for MIMO systems assume that the receiver has access to the channel data with infinite resolution. In practice, a quantizer is applied to the receive signal, so that the channel measurements can be processed in the digital domain. While the discrete-time nature of digital communications is presently well understood, the challenges arising from quantization have been largely neglected by the research community. There are two main reasons for explaining this phenomenon. First, the serious nonlinearity caused by coarse quantization complicates the theoretical analysis. Second, when the system is equipped with fairly high-resolution ADCs, the quantization error caused by the quantizer can be

neglected. However, when the number of antennas is gradually increased, it is not advisable to configure the system with high-resolution ADCs. Therefore, in order to reduce circuit complexity and save power and area, low-resolution ADCs have to be employed [121]. Figure 11 shows a receiver structure equipped with low-resolution ADCs. Each receiver antenna is connected with low-resolution ADCs, where the quadrature and in-phase elements of the received signal at every antenna are quantized separately. The output of quantization is used for digital baseband processing.

Since low-resolution ADCs can bring significant improvements in system power consumption, wireless communication in low-resolution quantization scenarios is extremely attractive. However, it is inevitable to face the dilemma of receiver performance degradation caused by coarse quantization. Therefore, some early work has carried out a series of discussions on the performance of receivers under the quantized system. Blazquez et al (2003) [122] conducted a performance analysis of the UWB radio receiver. They pointed out that depending on the kind of signal received and the kind of environment, the ADC bit resolution can be scaled to optimize power consumption. They also indicated that pulsed UWB signals need only 1 bit or 2 bits in the presence of AWGN channels to be sufficiently close to the non-quantized case, and 4 bits are required in the presence of a narrowband interferer. Hoyos et al. (2005) [123] reported several one-bit ADC receiver schemes: fixed reference, stochastic reference and sigma-delta modulation. For an AWGN channel, they demonstrated that the sigma-delta modulation scheme with oversampling can achieve the BER performance of a full resolution digital receiver. Mezghani et al. (2007) [124] studied the effect of quantized output signals on linear MMSE filters and Wiener filters. They showed that the joint optimization of the quantizer and the linear receiver can exhibit better BER performance than the conventional Wiener filter. Kazutaka et al. (2008) [125] evaluated the performance of optimal signal detection using the quantized received signals of a linear vector channel. In their work, the dimensions of channel input and output are both sent to infinity while their ratio remains fixed. The results revealed that for a noisy channel, the detection ability of the optimal detector decreases as the quantization step size increases. Ke et al.



(2008) [126] investigated the problem of quantization thresholds for finite-resolution digital receiver in UWB communication system. They indicated that 3-level receiver can acquire 1dB gain over monobit receiver and 8-level receiver can achieve a performance 0.2dB within that of the matched filter receiver. Yin *et al.* (2010) [127] explored the monobit digital receiver with an oversampling rate. In their research, the iterative algorithm is used to improve receiver performance. Compared to full-resolution matched-filter receivers, the receiver designed by iterative method has only 2dB SNR loss in AWGN channels and 3.5dB SNR loss in standard fading channels.

Although coarse quantization imposes severe nonlinearity on signal detection, its performance impairment to the receiver is still within acceptable limits. To mitigate the adverse effects of coarse quantization, Mezghani *et al.* (2010&2012) [128], [129] proposed a belief propagation-like detector and an iterative detector, respectively. In [128], the belief propagation-like algorithm is used for computing the marginal distribution of each signal component. Then, a state evolution formalism was propounded to evaluate the performance of belief propagation-like algorithm. It was shown that the proposed approach achieves good performance with low-resolution ADCs. In [129], the authors combined iterative equalization with decoding technique for coded data transmission. With the aid of an iterative decision equalizer, the proposed method is able to cancel iteratively the interference from the received signal. The simulation results indicated better performance in terms of BER than the previously designed filter especially for large number of antennas. However, the aforementioned work on quantized MIMO [128], [129] was restricted to point-to-point communications.

For signal detection in multi-user scenarios, the following literature has carried out a series of related work. Wang *et al.* (2014) [130] designed an iterative multiuser detector for uplink large-scale MIMO. In their work, the multiuser detection problem is relaxed as a convex optimization problem. Then, they solved the convex problem by using nonmonotone spectral projected gradient method. Compared with the MMSE detector, the proposed detector has lower computational complexity, and is more suitable for hardware implementation. In [131], Wang *et al.* (2014) further put forward a message-passing algorithm-based multiuser detector. The contribution of this approach is to reduce the overhead of channel matrix inversion by using message passing algorithm. However, the convex optimization process in [130], [131] is optimized separately for each constellation. The above work was later extended to arbitrary constellations in [132]. Wang *et al.* (2015) developed a phase-only generalized approximate message passing detector. In their work, they simplified the detection problem into a phase-only generalized approximation message passing detection problem by the central limit theorem and Taylor expansions. Then, the quantized phase measurements and signal prior probability distribution can be exploited in a Bayesian man-

ner in the detector. The proposed detector approaches to the ML detection performance, but it will experience the performance degradation with channel direction information when SNR is low. In the same year, Wang *et al.* [133] advocated a low-complexity message passing de-quantization detector. Similar to their previous work [132], they simplified the detection problem by the central limit theorem and the Taylor expansions. The difference is that they reduced the adverse effects of channel correlation through the LS estimation method. It has been proven that the proposed detector significantly outperforms the linear detector and works steadily even under strong antenna correlations. In 2016, Choi *et al.* [89] proposed a near ML detector. In their research work, the exhaustive search over all the possible transmitted vectors required in the original ML detection problem is first relaxed to formulate an ML estimation problem. Then, they converted the ML estimation problem into a convex optimization problem. Numerical results demonstrated that the proposed approach is efficient enough to simultaneously support multiple uplink users adopting higher-order constellations. Particularly, their work has provided a complete low power solution for the uplink of a massive MIMO system. Wen *et al.* (2016) [92] developed a GAMP-based joint channel-and-data algorithm. In their work, they modified the bilinear GAMP algorithm [100] and adapted it to the quantized MIMO system. However, the algorithm introduced in [92] is dedicated to the data detection for general MIMO channels rather than for the quantized OFDM channels. For the multi-user detection under the frequency selective wideband channels, Studer *et al.* (2016) [134] developed a new detection algorithm for quantized massive MIMO-OFDM. In their work, the main difficulty they face is how to solve the large-dimensional convex optimization problems. By introducing low-complexity numerical methods, they effectively solved the convex optimization problem in quantized detection. Moreover, their method enables low-cost and low-power massive MU-MIMO-OFDM system implementations that achieve near-optimal performance.

Nevertheless, most of the aforementioned work is mainly concerned with frequency-flat fading channels and low-frequency massive MIMO systems. In fact, in a low-frequency massive MIMO system, an increasing number of receiving antennas is robust against coarse quantization. Besides, a traditional linear detector is competent. However, in mmWave MIMO systems, limited RF chains are in the receiver, which means that observations are limited. Therefore, some of the latest references focused on studying the optima detection in mmWave MIMO quantization systems. In [135], [136] (Wang *et al.* 2016&2017), an optimal and computationally tractable data detector based on Turbo iteration principle was proposed for the mmWave quantized SISO-OFDM system. Their method converges rapidly and only a small performance loss is incurred. Besides, the high-quality CSI can be acquired without significant pilot overhead. In [137], [138], He *et al.* (2017&2018) propounded a generalized expectation consistent signal recovery algo-

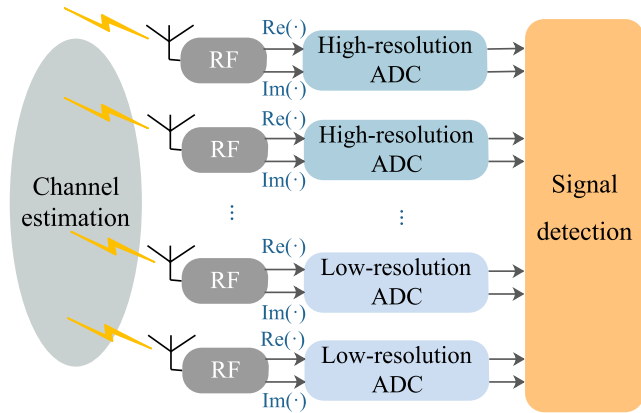


FIGURE 12. The mixed-ADC architecture receiver.

rithm to achieved Bayes-optimal data detection. In their work, the generalized expectation consistent signal recovery technique is mainly used to estimate the signal from the nonlinear measurements of a linear transform output. Moreover, the proposed method has an excellent agreement with the theoretical Bayesian-optimal estimator derived using the replica method.

In addition, a massive MIMO receiver with pure low-resolution ADCs suffers from considerable rate loss in the high-SNR regime. When all ADCs have low resolution, time-frequency synchronization and channel estimation are challenging and require excessive overhead [139]. Therefore, the mixed-ADC receiver architecture has received extensive attention from researchers. Figure 12 depicts a mixed-ADC receiver architecture in which some of the receiver antennas are connected to high-resolution ADCs. In [140], [141], Liang et al. (2015) proposed a mixed-ADC receiver architecture for MIMO system, in which a fraction of the ADCs has full-resolution to promote system performance, and the others have low-resolution in consideration of the hardware cost and energy consumption. Their results showed, for both single-user and multi-user scenarios, the mixed-ADC architecture with a relatively small number of high-resolution ADCs is able to achieve a large fraction of the channel capacity of conventional architecture, while reduce the energy consumption considerably. An optimal data detector for mixed-ADC massive MIMO is proposed in [142] (Zhang et al., 2015) by exploiting probabilistic Bayesian inference. In their proposed receivers, they established a prior distribution for the transmitted data and a likelihood function for the statistical model of receiver signals. Upon adopting the true prior and likelihood functions, the Bayes detector can achieve the best estimate in the mean squared error sense. In addition, more details on the performance and advantages of mixed-ADC receivers are in [38]–[40].

It is worth noting that many of the existing 1-bit ADC MIMO detectors have poor performance for coding systems despite their attractive uncoded performance, as their hard-decision outputs degrade the performances of the following channel codes. To solve this problem, Hong et al.

(2017) [143] explored a novel soft-output detector. In this method, the soft values are derived from the hard-decision observations by exploiting a novel distance measure, named weighted Hamming distance. Therefore, the soft-output detector can be naturally incorporated into a state-of-the-art soft channel decoder. In [144], Cho et al. (2017) designed a successive-cancellation-soft-output detector. They enhanced the soft-output detector in [143] by exploiting a priori knowledge. The main idea of the proposed detector is that the previously decoded messages are exploited to improve the reliabilities of the soft inputs of a subsequent channel decoder. Simulation results showed the performance of the proposed detector is excellent for the coded MU-MIMO systems with one-bit ADC. Kim et al. (2017) [145] proposed a novel MU-MIMO detection method. In their work, they propounded a soft-output weighted minimum distance decoding to computes soft metrics from one-bit quantized observations. Then, the complexity of the proposed approach is reduced by introducing hierarchical code partitioning. The results demonstrated that the proposed method significantly outperforms the other MIMO detectors with hard-decision outputs. In addition, the signal decoding techniques for low-resolution ADCs MIMO-CEM are reported in [146]–[148]. Doaa et al. (2016) [146] designed a low complexity sphere decoder. In their method, the baseband MIMO-CEM is used to define the sphere radius and enumerate the candidate sequences laying within the sphere. Then, the maximum likelihood decoder is used to pick up the candidate that most likely to be transmitted. In [147], Doaa et al. (2017) further constructed an adaptive sphere decoder based on an affine linear transformation model. Compared with the method in [146], the biggest difference of the proposed decoder is that the initial spherical radius can be adaptively adjusted based on the SNR condition. Therefore, the redundancy in the selected candidates can be greatly reduced, thereby reducing the computational complexity. Hany et al. (2018) [148] put forward a sparse maximum likelihood decoder. In their solution, a kernel sparse selector based on the correntropy maximization is used to nominate number of candidates from the space of linear baseband maximum likelihood decoder. The proposed decoder can achieve a complexity reduction by 91% compared to the recently decoder algorithms in [146], [147].

#### IV. HARDWARE IMPAIRMENTS AND TYPICAL APPLICATION SCENARIOS WITH LOW-RESOLUTION ADCs

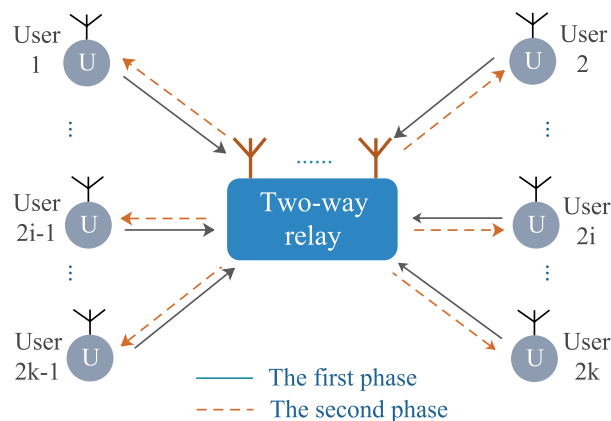
In the process of signal processing, coarse quantization can cause serious nonlinearity, which can be regarded as a kind of hardware impairments for wireless communication systems. Therefore, in this section, we first focus on the impact of hardware impairments on the actual design of the communication system. Then briefly introduce three typical application scenarios for low-resolution ADCs: the relay system, the UWB system, and the mmWave massive MIMO system. By describing the application of low-resolution ADCs in different scenarios, we will demonstrate the huge advantages and application prospects of low-resolution ADCs.

**A. SYSTEM PERFORMANCE ANALYSIS WITH HARDWARE IMPAIRMENTS**

For practical implementation, it is very attractive to deploy large scale antenna elements with cheap, compact and power-efficient radio and digital-processing hardware. However, most works assume that ideal hardware is available at both the transmitter and receiver, which is unrealistic in practice, while the performance of practical MIMO systems is usually affected by transceiver hardware impairments, such as phase noise, I/Q imbalance, amplifier non-linearities, and quantization errors [149]. Therefore, it is of profound importance to theoretically investigate how much hardware impairments can the large scale MIMO system tolerate to achieve a certain achievable rate performance.

Some researchers have analyzed the impact of transceiver hardware impairments on MIMO system performance. In [150], Christoph et al. (2010) studied the generalized MIMO channel with transceiver impairments. In their work, they demonstrated the residual distortions can severely degrade the performance of (near) optimum MIMO detection algorithms and proposed Tx-noise whitening to mitigate this performance loss. On the basis of [150], Emil et al. (2013) [151] showed that physical MIMO channels have a finite upper capacity limit due to the distortion from transceiver impairments. Nevertheless, the relative capacity gain of employing MIMO is at least as large as with ideal transceivers. As a further extension of the work in [151], Zhang et al. (2014) [152] found that by increasing both the number of transmit and receive antennas, the ceiling vanishes and the capacity can increase unboundedly at any SNR. In [153], Emil et al. (2014) further pointed out that the MIMO capacity is mainly limited by the hardware at the single-antenna user equipments. Moreover, the impact of impairments in the large scale arrays vanishes asymptotically and interuser interference becomes negligible.

The research work mentioned above mainly involves the Rayleigh fading channels. However, the validity of the assumption of Rayleigh fading is often violated in practical wireless propagation scenarios with the line-of-sight path. In [154], Zhang et al. (2015) investigated MIMO systems over Rician fading channels in the presence of transceiver hardware impairments. Their results showed that the achievable rate loss due to hardware impairments increases with the value of the Rician  $K$ -factor. For massive MIMO full-duplex relaying with hardware impairments, Xia et al. (2015) [155] proposed a low complexity hardware impairments aware transceiver scheme. In their work, the statistical knowledge of channels and antenna arrays at sources and destinations are exploited to mitigate the distortion noises. In [156], Liu et al. (2017) further studied the effect of hardware impairments on relay systems with amplify-and-forward (AF) scheme. They found that increasing the number of antennas enhances the system’s ability to tolerate hardware impairments, which facilitates the use of low-cost components in relay systems. Zhang et al. (2018) [157] investigated both uplink and downlink performance of cell-free massive MIMO with



**FIGURE 13.** The system model of multi-pair AF two-way relaying.

hardware impairments. In their work, they conceived a framework for performance analysis in cell-free massive MIMO with classical hardware distortion models and proposed a max-min power control algorithm to maximize the minimum user equipments rate. In addition, their work provides significant insights into the design of cell-free massive MIMO systems.

As can be seen from the aforementioned research work, hardware impairments indeed have a significant adverse effect on the wireless communication system, which not only reduces the achievable rate, but also weakens the communication quality between users. However, in the case of using a large-scale antenna array, the deterioration caused by hardware impairments can be compensated for. This also means that it is feasible to use low cost components in large-scale MIMO systems, such as low-resolution ADCs.

**B. RELAY SYSTEM WITH LOW-RESOLUTION ADCs**

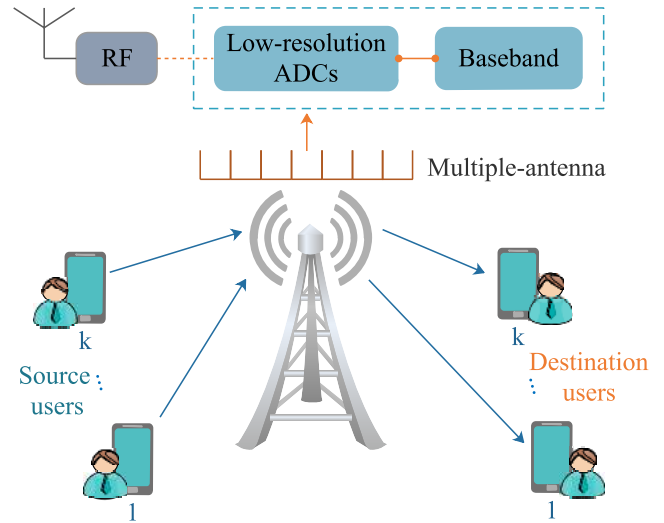
Relaying technologies can significantly improve transmission reliability, multiplexing gain and coverage, especially for cell edge users. For MU-MIMO networks, relay stations are widely deployed to improve the communication quality between the BS and the users. Figure 13 shows a typical multi-pair two-way relay system model in which  $K$ -pairs of users want to exchange each other’s information through a two-way relay with  $N$  antennas ( $N \gg 2K$ ), and each user is equipped with a single antenna.

On a parallel avenue, full-duplex relaying has received a lot of research interest, for its ability to recover the bandwidth loss induced by conventional half-duplex relaying. With full-duplex relaying, the relay node receives and transmits simultaneously on the same channel [158]. As such, full-duplex utilizes the spectrum resources more efficiently. In recent years, rapid progress has been made on both theory and experimental hardware platforms to make full-duplex wireless communication an efficient practical solution [159]. The benefit of improved spectral efficiency in the full-duplex mode comes at the price of loop interference due to signal leakage from the relay’s output to the input [160], [161]. How to overcome the detrimental effects of loop interference is

crucial for full-duplex operation. Yet, MIMO processing provides an effective means of suppressing the loop interference in the spatial domain. Suraweera et al. (2013) [162] showed that the relay system can benefit from the use of very large antenna arrays, which is beneficial for reducing loop interference, and analyzed several antenna selection schemes for spatial loop interference suppression in a MIMO relay channel. Further extension as reference [162], Ngo et al. (2014) [163] proposed ZF and MRC/MRT techniques to reduce significantly the loop interference effect in a multipair decode-and-forward relay channel.

Cooperative communication is a new technology that extends coverage, improves diversity, and reduces power consumption. In the field of cooperative communication, two-way relaying is widely studied. Two communication nodes exchange information by means of intermediate relays [164], [165], and use network coding technology. Therefore, compared with one-way relaying, two-way relaying can improve spectrum efficiency, and multi-pair two-way relaying is extension of two-way relaying [166]. Cui et al. (2014) [167] revealed that very large antenna arrays in two-way AF relaying system can average the small-scale fading, reduce the transmit power and mitigate the inter-pair interference. For the performance of multi-way relay networks with massive MIMO, Amarasuriya et al. (2014) [168] showed that very large antenna arrays at the relay can achieve substantial spectral and energy efficiency gains, while the transmit power at the user nodes and relay can be made inversely proportional to the number of antennas at the relay simultaneously. Jin et al. (2015) [169] demonstrated that the ergodic rates increase as the number of antennas of the relay station increases, but decrease as the number of user pairs increases. Different from the work of the above references, Amarasuriya et al. (2015) [170] further investigated the performance of massive MIMO-enabled multi-user relay networks. They showed the asymptotic SINRs and sum rates are independent of the fast fading component of the wireless channel. Besides, the presence of co-channel interference neither affects the transmit power scaling laws nor degrades the asymptotic SINR. However, pilot contamination significantly limits the system performance.

All the aforementioned works assume that the full-resolution ADCs are employed at the relay. However, the increasing number of antennas contributes to high hardware cost and power consumption, which poses new challenges on the practical implementation of massive MIMO. Therefore, finite-resolution ADCs can be applied for the relaying systems to reduce the hardware power consumption. Figure 14 shows a typical multi-pair AF relaying system in which the relay antennas employ the low-resolution ADCs to reduce system power consumption. Jia et al. (2016) [171] focused on a physical layer secrecy constrained massive MIMO relaying systems and proposed a double-resolution ADCs scheme. The presented numerical results showed that it is an effective solution to replace the high-resolution ADCs with medium-resolution ADCs. However, the work of [171]



**FIGURE 14. Multi-antenna Multi-user relay system with low-resolution ADCs.**

is performed assuming that the user-to-relay is in the case of perfect CSI, and the effect of low-resolution quantization on channel estimation is also ignored. Jiao et al. (2017) [172] studied the multi-user full-duplex massive MIMO AF relaying system with low-resolution ADCs. They found that the low-resolution ADCs massive MIMO relaying system not only has the low power consumption, but also the high-performance gains. Moreover, the performance loss caused by both the low-resolution ADCs and loop interference can be compensated by increasing the numbers of antennas at relay. Liu et al. (2017) [173] investigated the multi-user relay network with massive MIMO with mixed-ADC at receiver. In their work, a tight approximation for uplink achievable rate was presented, which holds for arbitrary antenna and general ADC setups. Compared with ideal unquantized case, the asymptotic signal-to-interference-plus-noise ratio (SINR) is degraded by an explicit factor which can be interpreted as a parameter indicating the “effective” resolution of the mixed-ADC structure. It should be noted that the relay of [173] still uses a high-resolution ADCs. For multi-user massive AF relay uplinks, Dong P et al. (2017) [174] investigated the generalized power scaling laws and sum rate. The results showed that 2-3 bits quantization will only result in limited rate loss, and can achieve considerable sum rate performance. In addition, the sum rate can be kept constant by reducing the transmission power and the power of the relay station, thereby demonstrating the rationality of the relay station being equipped with a large-scale antenna array under low-resolution quantization. By using the identity matrix as the pilot matrix, the performance and the optimal relay power allocation for the full-duplex massive MIMO relaying system with low-resolution ADCs have been investigated in [175] (Kong et al., 2017). In their observations, they revealed deploying massive relay antenna arrays is an effective approach to compensate for the rate loss due to low-resolution ADCs at the relay. However, increasing the number of antennas

becomes ineffective to handle the rate degradation caused by low-resolution ADCs at the destination. In addition, despite the use of low-resolution ADCs, employing massive antenna array at the relay can also enable significant power savings.

Since the quantization noise at the relay is related to the input signals, the diverse user transmit power will induce a more general case. Motivated by the above concerns, Cui et al. (2018) [176] presented the performance analysis and power control schemes of a generalized multi-pair massive MIMO AF relaying system where the relay antennas employ low-resolution ADCs. Different from the work using identity matrix [175], in their work, the pilot sequences, which are applied for channel estimation, are selected from Hadamard matrix. Based on the asymptotic analysis, they found that the effect of low-resolution ADCs on data transmission will disappear when the number of relay antennas grows without bound. Furthermore, the joint user transmit power and relay power optimization is proposed to enhance the sum achievable rate of the quantized MIMO relaying systems. Kong et al. (2018) [177] studied a multi-pair AF massive MIMO relaying system with one-bit ADC and one-bit DACs at the relay. They found that the sum rate with one-bit ADC and DACs is  $4/\pi^2$  times less than that achieved by an unquantized system in the low power regime. Despite the rate loss due to the use of one-bit ADC and DACs, employing massive antenna arrays still enables significant power savings. In [178], Zhang et al. (2019) considered a more general architecture, where ADC and DACs with arbitrary resolution profile are employed at the relay to achieve a possibly higher rate. In their work, they focused on the achievable rate and power-scaling law of the system. Leveraging on AQNM, they presented a unified framework to derive the exact closed-form expressions for the achievable rate. In addition, by transforming the power allocation problem into a sequence of geometric programming problems, they proposed a low-complexity power allocation algorithm to compensate for the rate degradation caused by the coarse quantization.

According to the latest research results, they all have two common conclusions. First, having low-resolution ADCs on the relay antenna can significantly reduce system power and hardware costs. Second, the use of large-scale antenna arrays can effectively mitigate the adverse effects caused by coarse quantization. The relaying system in the low-resolution quantization background mainly focuses on power allocation, and the relationship between ADC resolutions, number of antennas, user transmit power, and sum rate is considered accordingly. For the research of power allocation strategy under joint optimization, some achievements have been made [176], [178]. However, for the mobile two-way relay in the field of cooperative communication, many references only consider the case of a single mobile relay, and a single mobile relay may not be able to carry a large-scale antenna array, so multiple mobile relays need to be considered to form a distributed antenna structure. There will definitely be channel errors when each mobile relay is equidistantly arranged. The assumption that the ideal CSI can be obtained

at both the transmitting end and the receiving end, which is obviously not realistic. Therefore, in the non-ideal channel, the CSI needs to be fully utilized to implement a dynamic and flexible relay position adjustment and power allocation scheme, so as to improve the system's sum rate. In addition, from the perspective of energy efficiency, the previous work on the single-hop quantization relaying system without energy efficiency constraints only considered the power consumption of the receiver. However, energy-efficient design only makes sense without sacrificing the user's rate. In order to make full use of the advantages of low-resolution ADCs, it is necessary to consider how to further optimize the total power consumption of large-scale MIMO relay systems while meeting the quality of service requirements of users.

### C. UWB SYSTEMS WITH LOW-RESOLUTION ADCs

UWB has caught a lot of attention due to its viable application in short-range high-speed communications. The impulse radio (IR) UWB, which uses extremely short-duration pulses to transmit information, is a popular UWB implementation technology for its low complexity and low power consumption [179]. Nevertheless, there are two main factors that limit the development of UWB. One is the extremely large bandwidth of IR-UWB makes the design of receivers full of challenges. The conventional receivers, which are based on the matched filter followed by a RAKE structure, cost high complexity as a result of the multi-path diversity in UWB channel. The transmitted reference receivers avoid the need of channel estimation [180]. However, such receiving technique requires delay lines which are difficult to realize in the analog domain for large bandwidth signal. The other is that all-digital receivers are limited by the ADC resolutions and power consumption. The Nyquist sampling rate for IR-UWB may be as high as tens of giga samples per second [181] which is hardly realizable and highly power consuming for high-resolution ADCs. Since the complexity and power consumption of  $b$ -bit high-speed flash ADCs increase at the speed of  $2^b$ , a possible solution is to use low-resolution ADCs [123], [182]. Figure 15 and Figure 16 respectively show a transmitted reference receiver with stochastic reference and a matched filter transmitted reference receiver with first order sigma-delta modulation, in which a one-bit quantizer is provided to reduce the power consumption of the system. The receivers shown in Figures 15 and Figures 16 have received extensive attention in earlier research on ultra-wideband receivers with low-resolution ADCs.

In [183], Hoyos et al. (2003) investigated the performance of mono-bit receivers. In their observations, they found the dithered reference approach yields little BER gain over a conventional fixed reference one-bit ADC implementation. In addition, the first-order sigma-delta modulation with a one-bit ADC and 5 times oversampling yields performance that is only about 0.1dB away from a full resolution matched filter receiver, which showed that the sigma-delta modulation scheme with oversampling can achieve the BER

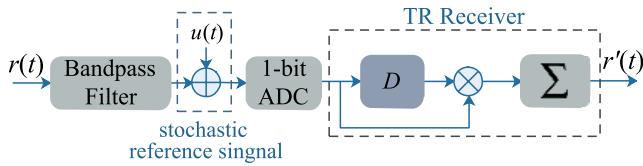


FIGURE 15. Mono-bit transmitted-reference receiver with stochastic reference.

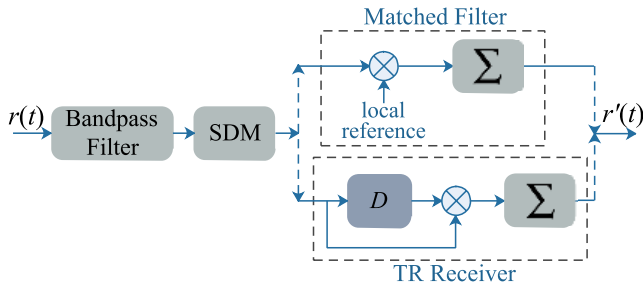


FIGURE 16. Mono-bit receiver with first order sigma-delta modulation.

performance of a full resolution digital receiver. In [184], Saberinia et al (2004) studied the resolutions of the ADC that is required for multi-band OFDM and pulsed-OFDM UWB systems. The performance of both systems is evaluated with different ADC resolution in realistic situations using the measured indoor propagation channel models provided by the IEEE 802.15.3a standard and compared to that of an ideal infinite resolution. The simulation results showed that in both systems four bits resolution are enough to a performance very near to the ideal case. To reduce the performance loss, sigma-delta modulation, which requires oversampling, can be applied. In [185], Puneet et al. (2005) studied the required ADC bit resolution for reliable transmission of UWB signals for a matched filter receiver. They demonstrated that four bits can give a close approximation to the optimal performance compared to the full resolution receiver. However, their analysis relies heavily on the assumption that the quantization noise can be modeled by a uniform random variable and a Gaussian assumption for the overall noise term. Exact performance analysis for an UWB direct-sequence spread spectrum system employing a matched filter receiver propagating over the AWGN channel is considered in [186]. It is found that with the appropriate dynamic range of the quantizer, three bits resolution is sufficient to closely approximate the infinite resolution case. Franz et al. (2005) [187] showed the generalized-likelihood ratio test based on the quantized samples can provide modest performance gains. This suggesting that conventional receiver structures can also be employed in the presence of a low-resolution ADCs. Moreover, their results revealed that four bits of resolution in combination with an optimal choice for the AGC gain are sufficient to closely approach the performance of an infinite resolution receiver.

In the aforementioned work, they are mainly concerned with the performance of UWB systems with low-resolution ADCs and the use of oversampling to com-

pensate for the impairments caused by coarse quantization. Regarding the design of low-resolution receivers under ultra-wideband, the following references explored a series of discussions. Gong et al. (2009) [188] considered the practical implementation of low resolution digital receivers in IR-UWB communication systems for low complexity and low power consumption. In their work, they derived the maximum mutual information per sample and proposed an optimal structure of the maximum likelihood receiver. Moreover, the BER performances under different modulation schemes are also studied. Their analysis demonstrated that the SNR degradation for one-bit receivers in multi-path UWB channel is only 1.96dB. To further simplify the receiver structure, Zhang et al. (2009) [189] proposed a monobit digital eigen-based receiver as a low complexity alternative to the eigen-based receiver. In their method, the received signal is decomposed into multiple dimensions based on the statistical characteristics of the received signal. Then, they collected the received signal energy by only exploiting the signal dimensions with larger eigenvalues. A significant advantage of the method they proposed is that the SNR at the receiver can be improved because channel noise is uniformly distributed over the multiple signal dimensions. Yin et al. (2010) [127] proposed a practically appealing suboptimal iterative receiver. The core idea of the proposed receiver is to refine the symbol detection with decision-directed weight estimation and removal of small sample points. Numerical simulations showed that compared with full resolution matched filter based receiver, the proposed receiver incurs only 2dB SNR loss in AWGN channels and 3.5dB SNR loss in standard UWB fading channels. A single-bit quantization receiver with phase rotation assistance was designed in [65] (Wang et al. 2013). In their work, they first derived the ML receiver and analyzed its performance in the form of deflection ratio to construct a suboptimal receiver for QPSK. Then, an eight-sector phase quantization scheme is employed to further eliminate the SNR loss caused by IQ imbalances. The simulation results showed that the proposed receiver greatly reduces the complexity with about 3dB SNR loss in AWGN channel and only 1dB SNR loss in dense multipath channels, compared with matched-filter based monobit receiver with perfect CSI. To mitigate the performance degradation caused by severe quantization noise due to employing monobit ADC, Khani et al. (2013) [190] proposed a low complexity suboptimal monobit receiver for transmitted-reference based IR-UWB systems. For this approach, the Marcum  $Q$ -function is used to estimate the suboptimal weights. Then the obtained weights are combined with the data samples. In both line-of-sight and non-line-of-sight channels, the proposed receiver can achieve a close-to-optimal BER performance without requiring perfect CSI. Of course, there are other references that involve the use of low-resolution ADCs in UWB systems. Their main research content is related to monobit receivers, as in the literature [191]–[194], we have not listed in more detail here.

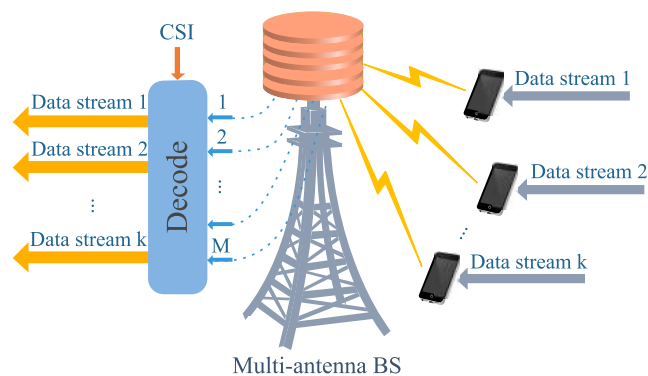


FIGURE 17. Massive MIMO system model.

From the contributions of the above references, we can see that most of their work is based on the case of one-bit quantization. In order to reduce the complexity and power, monobit sampling has attracted great attention because the power-hungry ADC can be replaced with the fast comparator. Compared with full resolution sample, monobit sampling not only achieves high sampling performance but also simplifies the system structure and decrease the power and cost. Thus, tradeoffs can be made between performance and complexity. It can be seen that the application of low-resolution ADCs to UWB systems greatly alleviates the embarrassing situation of the system in terms of power consumption and complexity.

**D. MILLIMETER-WAVE MASSIVE MIMO SYSTEMS WITH LOW-RESOLUTION ADCs**

The birth of massive MIMO technology has completely changed the pattern of traditional MIMO technology. It has the potential to enormously improve spectral efficiency by using its large number of BS transmit antennas to exploit spatial domain degrees of freedom for high-resolution beamforming and for providing diversity and compensating pathloss, thereby improving energy efficiency, data rates, and link reliability [195], [196]. During 2012 and 2016, academia and industry jointly launched the construction of massive MIMO prototype verification system. So far, the known massive MIMO prototype verification platform mainly includes Argos [197], [198] implemented by Rice University and Bell Laboratory, LuMaMi [199] built by Lund University and National Instruments and the 128-antenna system [200] established by Southeast University of China and National Instruments. The structure of massive MIMO system is shown in Figure 17. In addition, the EU, China, the United States, Japan and South Korea are particularly prominent in the research and development of massive MIMO.

MmWave massive MIMO springs as a technology that combines the prospects of the huge available mmWave bandwidth on the one hand, and the expected gains from massive MIMO antenna arrays on the other. When the mmWave massive MIMO technology is used in the Het-Net topology, next-generation mobile networks can be projected to reap the benefits of the three enablers (mmWave communication, massive MIMO and hyper-dense networks)

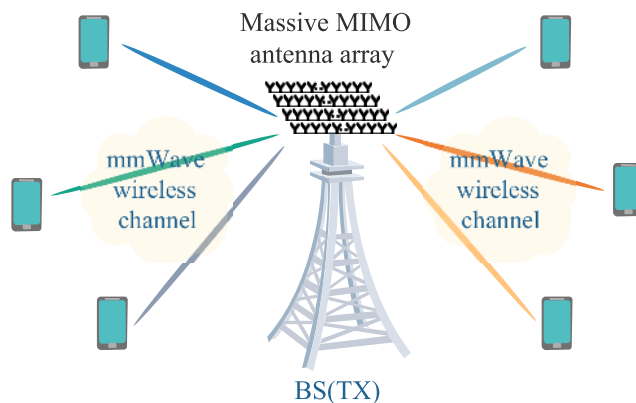


FIGURE 18. MmWave massive MIMO system model.

on a very large scale, and thereby support a plethora of high-speed services and bandwidth-hungry applications not hitherto possible [201], [202]. Figure 18 shows a single cell network mmWave massive MIMO system model which is composed of the transmitter, the wireless channel and the receivers. Although the potential of mmWave massive MIMO is exciting, the challenges that evolve span the broad fields of communication engineering and allied disciplines. With rapid urbanization and an accelerating number of cellular-enabled devices per person, the density and physical environment these mmWave massive MIMO-based networks will face are new, and the challenges are immense and barely understood. The actual deployment of MIMO-based cellular systems [203]– [204] is extremely difficult to achieve.

For future mmWave mobile broadband systems, from Table 3 [202], analog/hybrid beamforming are considered to be a possible solution to the excessive power consumption at the receiver. Due to the large bandwidth, high-resolution ADCs have a significant amount of power. Therefore, they are considered to be a major contributor to the power consumption of a mmWave receiver. The application of low-resolution ADCs in mmWave massive MIMO systems has alleviated this dilemma. In most cases, the low-resolution ADCs digital beamforming is most energy efficient. Hybrid beamforming can also be combined with low-resolution ADCs. Of course, low-resolution ADCs bring some advantages to the system, but also bring some unfavorable factors. In addition to some of the key technologies discussed in Sections II and Section III that involve mmWave systems, we will briefly discuss the beamforming techniques in mmWave massive MIMO systems with low-resolution ADCs from the perspective of actual system power consumption to demonstrate the enormous potential of low-resolution ADCs.

One possible architecture to reduce the number of RF chains is hybrid beamforming in which the overall beamformer consists of a concatenation of an analog RF beamformer implemented using phase shifters and a low-dimensional baseband digital beamformer. However, conventional hybrid beamforming designs require high-resolution phase shifters, which are expensive. Sohrabi et al. (2015) [205] proposed a heuristic transceiver equipped

TABLE 3. Comparison of precoding techniques.

Features	Analog Beamforming	Digital Precoding	Hybrid (Analog-Digital) Precoding
Number of streams	Single-stream	Multi-stream	Multi-stream
Number of users	Single-user	Multi-user	Multi-user
Signal control capability	Phase control only	Phase and amplitude control	Phase and amplitude control
Cost	Least	Highest	Intermediate
Performance	Least	Optimal	Near-Optimal
Energy consumption	Least	Highest	Intermediate
Hardware requirement	Least; one RF chain only	Highest; number of RF chains equal number of transmit antennas	Intermediate; number of RF chains less than number of transmit antennas
Suitability for eaves- sive MIMO	Unsuitable; no amplitude control, no multi-user	Impractical; prohibitive cost and high energy consumption	Practical and realistic

with finite-resolution phase shifters. In their work, they addressed the challenge of limited transmit/receive RF chains by considering a two-stage hybrid digital and analog beamforming architecture. It was shown that the proposed hybrid beamforming design can achieve a rate close to that of optimal exhaustive search. Mo et al. (2016) [206] considered the generalized hybrid architecture with a small number of RF chains and arbitrary resolution ADCs. For this architecture, they analyzed the spectral efficiency and derived the achievable rates with channel inversion and SVD based transmission methods. They showed that the achievable rate of this architecture is comparable to that achieved by full-resolution ADCs receiver at low and medium SNR. Lin et al. (2016) [207] introduced an architecture of hybrid precoding that involves analog beamforming and digital precoder in downlink multiuser mmWave MIMO system. In their work, a low complexity beam selection algorithm for efficiently maximizing system energy efficiency using limited feedback information from the users was proposed. In particular, the use of one-bit ADC at the receiver is considered in order to reduce power consumption. Their approach can achieve the maximum energy efficiency by adaptively choosing the best RF chain configuration. Different from the work mentioned above, Abbas et al. (2016) [208] were skeptical about the conventional wisdom that hybrid combining is preferable over digital combining. Rather, the relationship between digital combining with few bits and hybrid combining is critically determined by mmWave channel parameters and component power consumption parameters. Therefore, they provided a comprehensive power-consumption comparison method and proposed a performance chart technique that allows to choose between hybrid combining and digital combining depending on the given component parameters.

Roth et al. (2017&2018) [209]–[211] conducted a series of detailed studies on mmWave beamforming with low-resolution ADCs. In [209], the spectral and energy efficiency based on the RF-frontend configuration were compared. They showed that low-resolution ADCs digital beamforming systems are more energy efficient and

achieving a higher rate than hybrid beamforming systems for the given scenarios, especially in the low to medium SNR region. Besides, if the imperfections of the AGC is in the range of  $-20\%$  to  $20\%$ , there is no major influence on the performance. In [210], the performance of digital beamforming with low-resolution ADCs based on link level simulations was investigated. In their observations, they found that the complexity of MMSE equalization is dominated by the computation of the gram matrix and not the matrix inversion. In addition, they showed that it is possible to achieve high data rates with digital beamforming mmWave system with low-resolution ADCs by considering low complexity algorithms. In [211], for hybrid beam forming and digital beam forming with low-resolution ADCs, the spectral and energy efficiency of both systems under practical system constraints were compared. The evaluations showed that low-resolution ADCs digital beamforming systems are more energy efficient and achieves a higher rate than hybrid beamforming systems for multiuser scenario. The reason is that the sub-arrays of hybrid beamforming must focus on a single user. To improve the spectral and energy efficiency, Choi et al. (2017) [212] reported the hybrid MIMO receiver architecture with resolution-adaptive ADCs. In their architecture, the array response vectors are employed for analog beamforming, and the quantization distortion of received signals is minimized by leveraging the flexibility of ADC resolutions. The proposed architecture provides useful insights into the design of future mmWave base stations. Choi et al. (2019) [213] further proposed a two-stage analog combining architecture. They split the solution into a channel gain aggregation stage and a gain spreading stage by using array response vectors and discrete Fourier transform matrix, respectively. Then, in the two-stage analog combiner, the mutual information between the transmitted and quantized signals can be optimized by effectively managing quantization error. Yang et al. (2018) [214] established a low-resolution ADCs module assisted hybrid beamforming architecture. In their method, the electronic switch on the transceivers sweeps between the low-resolution



ADCs module and the hybrid beamforming module, during the beam training phase, the transmitter switches to the hybrid beamforming module and the receiver switches to the low-resolution ADCs module. Therefore, the proposed architecture was low-cost and hardware realizable. The simulation results verified the proposed hardware system architecture can successfully accelerate the millimeter-wave link establishment without degradation in the data transmission performance. In addition to beamforming, some details on user scheduling in mmWave systems with low-resolution ADCs can be found in [215], [216].

From the latest research on precoding of mmWave systems with low-resolution ADCs, it can be seen that the large number of antennas and high-power consumption of transceivers, along with the increasing hardware complexity, induce challenges to existing beamforming techniques. Most of the traditional mmWave architectures rely on analog beamforming, which is time-consuming because it can only use one beam direction at a time [217]. Hybrid beamforming system architecture can provide variable and multi-directional scanning simultaneously [218]. However, in hybrid precoding architectures, quasi-omnidirectional beam scanning creates problems to the receiver because of the high computational complexity and the requirement of phase shifters with large number of quantization bits. A low-resolution ADC architecture can reduce substantially the power consumption and computational complexity at the receiver. The two most critical challenges in precoding are the acquisition of CSI and precoding matrices. Due to the use of large-scale antennas, the channel matrix and precoding matrix dimensions are increased, and the complexity of the algorithm, the hardware cost of the system, and the difficulty of implementation are increased. Therefore, in order to provide a substantial performance improvement for realistic quantized MIMO systems by employing transmit precoding, it is necessary to study in-depth the channel model in line with practical application scenarios. Equally important, the existing research on large-scale MIMO system precoding technology is mostly limited to single-antenna user scenarios, and it is meaningful to extend it to multi-antenna user scenarios.

## V. DISCUSSION ON SOME CHALLENGES AND FUTURE RESEARCH DIRECTIONS AND RECOMMENDATIONS

This section discusses the general and specific restrictions as well as technical challenges of low-resolution ADCs applied in wireless receiving processing. In response to these challenges and limitations, some potential implementation methods are presented to address these dilemmas. In addition, some meaningful future research directions concerning low-resolution ADCs applied in wireless communication systems are presented as follows.

### A. GENERAL RESTRICTIONS AND CHALLENGES

A crucial problem with modern ADC is that the power dissipated per conversion step increases dramatically for sampling rates higher than about 100 MHz [219]. This implies that,

for wideband communication systems, the resolution of the ADC must be kept low to maintain a power budget that is within acceptable levels. It is worth noting that in UWB and mmWave systems, the motivation for using one-bit ADC is the large bandwidth of the transmitted signal. In particular, another important reason is the large-scale number of RF chains on BSs in large-scale MIMO systems, which makes the use of low-cost solutions attractive.

To alleviate this predicament, we can employ several high-resolution, low-speed sub-ADC operating in parallel. However, this ADC structure may impose error floors on the system's performance due to the mismatch among the sub-ADC. Another option is that we can choose high-speed but low-resolution ADCs to decrease both the power consumption and the hardware cost. Unfortunately, the performance of quantized massive MIMO systems with low-resolution ADCs is lower than that of the idealized system operating without quantization. Besides, the optimal distribution of the transmitted signal has to be designed to achieve the capacity of continuous memory-less channel. However, the channel capacity of realistic systems using low-resolution ADCs is approached by the discrete input distribution [26]. The optimal signaling alphabet distribution of low-resolution ADCs using more than one bit remains an active area of research, especially for the mmWave channel.

The trade-off between ADC resolutions and ADC power consumption is important to improve energy efficiency. In [220], we learn that more antennas should be selected for reception with a low bit resolution in the low SNR regime, while a few antennas should be active with a high bit resolution in the high SNR regime. Moreover, the optimal number of active antennas and the optimal bit resolutions depend heavily on the average receive SNR. Therefore, choosing the appropriate quantization resolution is extremely important for the energy efficiency of multi-antenna systems, which is directly related to the application of the actual system. Of course, another major challenge should also be included is to find the optimal thresholds of the ADC quantizer for maximizing both energy efficiency and spectral efficiency.

Since AQNM can effectively overcome the nonlinear effects caused by coarse quantization, many existing conclusions about performance analysis are based on this quantized output model. In the low SNR region, the accuracy of AQNM is sufficient. This is because the multi-antenna array at the transmitting end makes the correlation between the elements among the distortion error  $e$  is weak, so using AQNM to analyze system performance does not cause significant errors. However, at high SNR, the model is not accurate enough due to three reasons [12]. First, the input signal obeys the continuous Gaussian distribution. Second, the quantization noise is also assumed to follow Gaussian distribution. Third, the Max-Lloyd quantizer of the ADC minimizing the mean square error is not necessarily optimal in terms of maximizing the system's capacity. Therefore, it is difficult to obtain accurate performance analysis with AQNM in a high SNR region. In addition to the three reasons mentioned in [12], there are

two additional factors that we believe may cause AQNM to be less accurate. One is that the transmitter is only equipped with a small number of antennas, and the other is that the ADC resolution is very low. These all increase the correlation between the elements in the distortion error  $e$ , which in turn causes a large error in the AQNM.

### B. SPECIFIC LIMITATIONS AND CHALLENGES

In the previous section, we described the challenges of using low-resolution ADCs in systems from a system performance perspective. Aiming at giving an integral illustration, the specific limitations and challenges will be discussed in this subsection as a supplement of the general case. We know that low-resolution quantization will inevitably lead to severe nonlinearities, which is a huge challenge for signal processing. The accurate knowledge of the CSI is essential for realizing the promising gain of systems, which is usually acquired by using pilot symbols. However, due to the severe nonlinearity caused by coarse quantization, it is unrealistic to obtain perfect CSI on the quantized receiver. So, the channel coefficients are needed to be trained with employment of conventional channel estimation techniques, which means that the training sequence should be long enough for ensuring a reliable CSI estimation. Although many channel estimators have recently been proposed (e.g., EM estimator and near ML estimator), the training overhead of conventional channel estimators still remains excessive. One possible solution is to employ joint channel-and-data estimation or decision-directed channel estimation. However, this further increases the complexity of the channel algorithm.

Under the influence of coarse quantification, we note that the classical detection theory for traditional unquantized system becomes no longer applicable in the coarse quantization scenario. Therefore, effective new signal detection algorithms have to be constructed for counteracting the detrimental effects of low-resolution ADCs and to exploit the sparsity of channel impulse response. However, to our best of knowledge, much of the current research work on quantified systems does not involve the use of sparsity.

### C. POTENTIAL IMPLEMENTATIONS FOR GENERAL AND SPECIAL CHALLENGES

In Section A, we pointed out the challenges of using low-resolution ADCs in actual systems, and also illustrated the shortcomings of the AQNM from the perspective of channel modeling. In Section B, we explained from the perspective of the physical layer that coarse quantization would make CSI difficult to obtain accurately, and the conventional channel estimation algorithm and detection algorithm are no longer suitable for low-resolution quantization scenarios. In this section, we will present some suggestions and methods for some of the challenges and limitations mentioned above.

#### 1) FOR CHANNEL MODELING

Given that the AQNM model is not accurate enough in SNR regions, a potential way to improve this phenomenon is to

use a model based on Busgang decomposition and consider the correlation between the elements in the quantization distortion matrix. Since the effect of quantization distortion  $e$  is not neglected, this channel model is more accurate than AQNM in the case of a high SNR region or a small number of antennas. Moreover, for the performance analysis of the pure low-resolution ADC architecture and the mixed-ADC architecture, the model can reduce the analysis error.

#### 2) FOR RECEIVER ARCHITECTURE

The use of high quality data for channel estimation and signal detection is attractive because in low-resolution quantization systems, the received data experiences severe distortion in both amplitude and phase.

- 1) To alleviate the huge overhead caused by synchronization, channel estimation, precoding, etc., a straightforward approach is to use a receiver with a mixed-ADC architecture. Compared to pure low-resolution ADC architectures, the mixed-ADC architecture can cyclically utilize high-quality signals to aid channel estimation so that more accurate CSI can be acquired. In addition, accurate CSI is very beneficial for the setup of the precoding matrix, which is especially important to further reduce the hardware cost while improving system energy efficiency and spectral efficiency. The mixed-ADC architecture is a general receiver architecture with practical commercial value.
- 2) Combining the BA algorithm conduces to enhance the flexibility of the mixed-ADC architecture. Without losing the communication quality between users, a new approach to further reduce system cost and improve energy efficiency is to adjust the resolution of the high-resolution ADCs by BA algorithm while maintaining a certain number of low-resolution ADCs. Unlike the mixed-ADC architecture, which forces antennas to select between 1-bit and  $\infty$ -bit ADCs, the use of the BA algorithm for resolution-adjustment of high-resolution ADCs contributes to extend the receiver architecture to more general situations.

#### 3) FOR PHYSICAL LAYER

The focus of the physical layer is mainly on synchronization, channel estimation, precoding, signal detection and so on. A major limitation in low-resolution quantization systems is how to obtain accurate CSI. Moreover, in order to overcome the nonlinear distortion caused by coarse quantization, many existing physical layer methods have very high complexity and are not conducive to actual communication systems.

- 1) Sequences with strong autocorrelation (e.g., PN) can be used as a training sequence for synchronization and channel estimation. In the observations of our previous work [69], the autocorrelation of sequences such as PN sequences does not appear to be affected by coarse quantization. Therefore, this property can be utilized in channel estimation over the time-domain,

which is more attractive than channel estimation in the frequency-domain based on comb pilots. In addition, this autocorrelation can also be used for frame synchronization.

- 2) Regarding the problem of high complexity of existing estimation algorithms, an effective method to solve this dilemma is joint channel sparsity and introduce compressed sensing, especially for millimeter wave channels. In the frequency band above 6 GHz, the channel approaches the sparse channel, and the compressed sensing method can be used to reduce the complexity of the channel estimation algorithm.

With regard to the problems faced in low-resolution quantization systems, we propose some potential implementation methods to improve these shortcomings from the perspectives of channel modeling, receiver architecture and physical layer. Of course, the effectiveness and feasibility of these methods need to be further explored.

#### **D. NEW RESEARCH DIRECTIONS AND RECOMMENDATIONS**

In this section, a series of meaningful future research directions of low-resolution ADCs and recommendations in wireless communication systems are illustrated as follows. In view of the challenges currently encountered in quantized communication systems, we will discuss future research directions in the field of low-resolution quantization communication from nine aspects.

##### **1) RELAY FORWARDING TECHNOLOGY WITH LOW-RESOLUTION QUANTIZATION**

For large-scale MIMO systems with mixed-ADC/DAC architecture, there is currently no universal solution for obtaining channel estimation performance comparable to that of a full RF link with a lower overhead in the case of a limited number of RF channels. Furthermore, it is also possible to consider how to effectively obtain CSI under the mixed-resolution ADC architecture, and analyze the influence of the mixing ratio of high-resolution ADCs and low-resolution ADCs on channel estimation. Meanwhile, for a pilot-assisted quantized MIMO system, the system performance will depend on the selected pilot sequences. Therefore, the impact of few-bit ADC on channel estimation should be considered too. Of course, a more in-depth study of the channel correlation impact on the performance of the relaying system is intentional, and effective theoretical analysis of channel correlation will be a very challenging topic. In addition, the distributed antenna structure is an alternative and supplement to the centralized antenna structure. The distributed block antenna structure with low-resolution ADCs is also a key research direction in the future.

##### **2) AUTOMATIC GAIN CONTROL TECHNIQUE**

The ADC is a key component in the digital receivers. It converts analog signal into its digital format and directly affects the entire receiver performance. As the demand for speed and

bandwidth of communication system is increasing, the power consumption and conversion rate of ADC become a bottleneck for the development of modem receiver. Thus, how to design the receiver with low-resolution ADCs becomes an urgent problem. In general, the system of single-bit quantization and finite-resolution quantization does not need to consider AGC at present, which indirectly hinders the research progress of AGC under low-resolution quantization. Therefore, the existing references on AGC under low-resolution quantization are very rare, and the research work of AGC under low-resolution quantization is still in the initial stage of theoretical research.

In addition to the study of gain control for PAM, we should also consider the larger constellations and investigate the performance that can be achieved over fading and dispersive channels. Besides, complete transceiver designs for ADC-constrained systems also require algorithms that combine AGC with other receiver functionalities such as carrier and timing synchronization. In general, there is still a long way to go to realize the perfect gain control of the signal in the actual system in the future.

##### **3) SYNCHRONIZATION TECHNOLOGY**

From the current algorithm for estimating the joint CFO and channel, we can see the importance of synchronization in low-resolution quantized systems. Methods that are compressive and robustly estimate the channel against synchronization impairments are limited. In practice, the carrier frequencies between the local oscillators at the transmitter and receiver can be mismatched, which results in CFO impairing the phase of the channel measurements in systems. Therefore, synchronizing the received signals is necessary for the system.

However, the development of synchronization techniques at low-resolution quantization is not as good as it has been developed in unquantified scenarios. Most of the current research is to study how to quantify the phase, and all of them are theoretical discussions. There are still very few specific synchronization measures. In addition, research on phase compensation is still very rare, and now more attention is paid to timing synchronization under low-resolution quantization, especially for frame synchronization. Given that OFDM system is very sensitive to CFO and may directly cause the system to malfunction. Therefore, in the future, a meaningful research direction is aimed at the synchronization study under the quantized OFDM system.

##### **4) CHANNEL ESTIMATION TECHNOLOGY**

It can be seen from the recent research progress of channel estimation that the magnitude and phase information about the received signal are seriously lost due to low-resolution quantization. Therefore, it is difficult for the transmitter and receiver to obtain perfect CSI, which requires us to pay more attention to how to design a suitable pilot sequence. With using different pilot sequences, we may get different channel estimation performance. Then, the next step can be to consider the pilot optimization problem in different case to

optimize the estimation performance. Since the requirement of long training sequences is a key obstacle of accurate channel estimation, greedy algorithms can be used for exploiting the mmWave channel statistics for circumventing this challenging problem. For the acquisition of CSI, in the mmWave system, the channel estimation problem of low-resolution quantized MIMO systems operating in mmWave channels can be formulated as a recovery problem of sparse signal, which could be efficiently solved by the powerful technique of compressed sensing.

With regard to the channel estimation algorithms currently proposed, these algorithms can be applied to different system architectures, but some algorithms do not incorporate the characteristics of channel propagation, such as sparsity. It is worth noting that the approximate sparsity and Doppler spread characteristics of the millimeter-wave band beam domain channel can be used to effectively reduce the pilot overhead required for channel information acquisition. It is necessary to further develop and improve the beam domain channel information acquisition technology in various typical scenarios. In addition, in the propagation characteristics of millimeter wave, direct wave transmission will become the dominant feature of channel propagation, and the channel estimation algorithm combined with the direct path propagation characteristics needs to be further improved in the future work.

For practical applications, although the channel estimator based on approximate ML estimation can improve the estimation performance and can better support high-order constellation modulation, in terms of computation, the estimator relies heavily on the ML algorithm and iterative algorithm. This will be detrimental to the practical application of the estimator in the system, so designing a low complexity channel estimator is especially important for low-resolution quantization systems. Finally, the academic research on the spatio-temporal correlations of channels at low-resolution is extremely scarce. Since spatio-temporal correlations can be used to improve system performance, the discussion of spatio-temporal correlations is very meaningful to channel estimation.

##### 5) CHANNEL STATE INFORMATION FEEDBACK

One possible effective approach in obtaining the channel condition in the transmit side is to use the explicit feedback from the receiver side, as illustrated in Figure 19. As opposed to exploiting the reciprocity, compensation for the RF difference is not necessary in this method. In order to warrant timely channel information, however, the feedback delay must be less than the coherence time.

For the feedback process, its feedback information should not be too large, otherwise it will affect the uplink data transmission. It is worth noting that the amount of feedback information increases with the number of antennas. Therefore, the overhead problem can become critical when it comes to multiple antenna systems. The estimated CSI at the receiver can be compressed to reduce the feedback

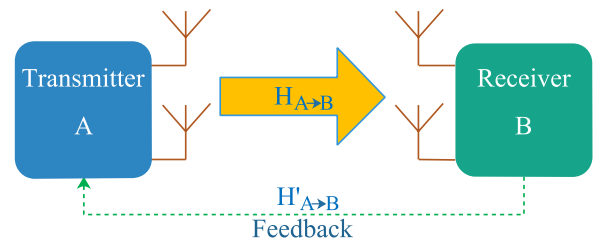


FIGURE 19. CSI feedback diagram.

overhead. Generally speaking, there are two methods, one is to quantize the channel gains and the other is to use the codebook that is shared by the transmitter and receiver. Since the coarse quantization makes the amplitude and phase severely distorted, the channel gain cannot be correctly represented by the low-resolution ADCs. Besides, for mmWave channel, the phase-invariant beamforming codebooks are no longer suitable. So, the design of the new feedback codebook must take into account the quantized phase information.

Given the importance of mmWave massive MIMO systems, the feedback codebook design combined with quantized phase information in low-resolution quantized scenarios is an interesting topic in future work. At the same time, considering the sparse characteristics of the mmWave channel, the feedback codebook design corresponding to the channel impulse response is also a direction worthy of further study.

##### 6) TRANSMIT PRECODING

The hybrid precoding design under the mmWave MIMO system faces three challenges: one is to design a low-complexity algorithm to obtain a precoding matrix, the other is to obtain CSI under severe distortion caused by low-resolution quantization, the third is to break the hardware limitations in the hybrid architecture to reduce the cost of the hybrid system and maximize system performance. Precoding design requires that the phase information of the channel matrix is quantized. Under the influence of coarse quantization, the channel state information obtained by the receiver and the transmitter is biased. Therefore, a corresponding channel estimation algorithm needs to be designed for a specific system, and the channel information is conditionally fed back. Of course, when designing the channel estimation algorithm, it is necessary to consider the transmission including the pilot, the design of the codebook, and the feedback method of the channel information. Since the optimal design of the transmit precoding matrix of the mmWave channel and the acquisition of the CSI depend on the actual scenario, it is particularly important to carefully consider the operating scenario of the system, especially in the case of a single user with low-resolution ADCs extending to multiple users. In addition, for the hardware limitation problem, the main consideration is how to balance the number of RF, or find other ways to replace RF, which is the direction that can be studied later.

##### 7) MIXED-ADC RESOLUTION ARCHITECTURE

Under low-resolution quantization we will face the following problems: unbalanced calibration of in-phase and

quadrature phases, loss of performance at high SNR, long pilot sequences, and so on. These problems will be moderately improved when using a mixed-ADC architecture [40], [140]. The quantization noise of channel estimation is reduced with the employment of high-resolution ADCs. Furthermore, the pilot overhead may also be reduced. Therefore, when a few ADC use high-resolution, we can better obtain the channel parameters, so as to better estimate the channel, thus reducing the performance loss of the system.

Of course, there is an important problem to be solved here, that is, how to determine the ratio of low-resolution ADCs and high-resolution ADCs in the system. It is worth noting that low-resolution ADCs are advantageous in low SNR regions, but not in high SNR regions. Therefore, in the mixed-ADC architecture, in addition to focusing on energy efficiency and signal detection performance, it is also necessary to consider the SNR condition.

#### 8) RECEIVER TECHNOLOGY

Low-resolution quantization brings serious nonlinearity to the receiver, resulting in huge performance loss in channel estimation, signal synchronization and other links, which directly affects the correct rate of signal detection. Classical signal detectors, such as the MRC, ZF, LS, MMSE, ML and the message passing detector have been widely used for idealized unquantized MIMO systems. However, the performance of these classic receivers erodes in the face of low-resolution ADCs. It is worth noting there is no straightforward technique of extending the results based on frequency-flat channels to wideband mmWave channels. In addition, high-order modulation is feasible under perfect CSI, but it is unrealistic to obtain perfect CSI under low-resolution quantization. How to support the transmission of high-order modulated signals under low-resolution quantization system is very interesting.

Furthermore, the existing receiver technologies with low-resolution quantization are very difficult to implement. These algorithms involve very complex nonlinear integration and iterative processes, which directly lead to complex circuit components in the receiver. This burden cannot be tolerated at all in commercial communication systems. How to reduce the complexity of the signal detection techniques and put them into the actual system is an urgent problem to be solved. The low-complexity MMSE detector using convex optimization may be investigated to reduce the computational complexity at the cost of an affordable error-rate performance degradation. In view of the transmission characteristics of millimeter waves, a potential direction for future research should also be included is to extend the ML detector both to frequency-selective mmWave channels and to sparse mmWave channels.

#### 9) MULTI-TECHNOLOGY INTEGRATION AND APPLICATION

With the development of communication technology, people can no longer meet the experience brought by the 4th generation mobile communication, and now the focus

has gradually turned to the 5G communication. The 5G network would not be developed to replace current wireless networks. It is rather to advance and integrate the existing network infrastructures with the new one [221]. Low-resolution quantization technology combined with massive MIMO technology has made a significant contribution to improving system efficiency and performance. Towards this end, the integration and application of these two technologies with other technologies is inevitable in the future. How to integrate low-resolution ADCs, massive MIMO, ultra-dense networking, non-orthogonal multiple access, new multi-carrier, mmWave transmission and other technologies will be a very meaningful and challenging task for future commercial systems.

#### VI. CONCLUSION

In this paper, a comprehensive overview of the low-resolution ADCs and its extensive applications in wireless receiving systems is presented. From our perspectives, the related work with low-resolution quantization can be categorized into three types, including system performance analysis under low-resolution quantization, specific signal processing methods and typical applications respectively. The effects of low-resolution ADCs on system performance are discussed through AWGN and AQNM output channels. Compared to conventional receivers equipped with high-resolution ADCs, the introduction of low-resolution ADCs can greatly increase energy efficiency with an acceptable performance loss. The related technical literatures regarding low-resolution ADCs are overviewed, involving AGC, synchronization, channel estimation, signal detection and receiver design. With the assistance of the coarse quantization technology, the power consumption of the system and the complex receiver structure can be effectively improved. As a typical application, the impact of hardware impairments on the system is first described, and then the development prospects and challenges of low-resolution ADCs under the relay system, UWB system and mmWave system are introduced. In addition, some general and specific limitations and technical challenges of low-resolution ADCs in signal processing for wireless communication are discussed in this paper. Aiming at the difficulties faced by low-resolution quantized communication systems, some potential implementations are presented from the perspective of channel modeling, receiver architecture and physical layer. After that, a series of meaningful research directions are presented to intensively encourage the increasing scholars to conceive innovative ideas and develop sophisticated methods. In the future work, the related research with low-resolution quantization will emphasize attaching more importance to conceive interested ideas and methods in the field of receivers. Influenced by green communication, high energy efficiency, high spectral efficiency, high transmission efficiency and low cost are the constant pursuit of academic community and business community. It is promising to exploit low-resolution ADCs in wireless receiving processing to promote the performance enhancement and refinement.

## REFERENCES

- [1] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, "What will 5G be?" *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.
- [2] T. Baykas, C.-S. Sum, Z. Lan, J. Wang, M. A. Rahman, H. Harada, and S. Kato, "IEEE 802.15.3c: The first IEEE wireless standard for data rates over 1 Gb/s," *IEEE Commun. Mag.*, vol. 49, no. 7, pp. 114–121, Jul. 2011.
- [3] A. Ghosh, T. A. Thomas, M. C. Cudak, R. Ratasuk, P. Moorut, F. W. Vook, T. S. Rappaport, G. R. MacCartney, S. Sun, and S. Nie, "Millimeter-wave enhanced local area systems: A high-data-rate approach for future wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1152–1163, Jun. 2014.
- [4] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5G cellular: It will work!" *IEEE Access*, vol. 1, pp. 335–349, 2013.
- [5] A. F. Molisch and M. Z. Win, "MIMO systems with antenna selection," *IEEE Commun. Mag.*, vol. 5, no. 1, pp. 46–56, Mar. 2004.
- [6] L. Guishan and Z. Wen, "Analysis and research on the influence of ADC error on system performance," *Meas. Control Technol.*, vol. 22, no. 4, pp. 52–55, 2003.
- [7] B. Widrow, "A study of rough amplitude quantization by means of Nyquist sampling theory," *IRE Trans. Circuit Theory*, vol. 3, no. 4, pp. 266–276, Dec. 1956.
- [8] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, Feb. 2014.
- [9] J. Singh, O. Dabeer, and U. Madhow, "Capacity of the discrete-time AWGN channel under output quantization," in *Proc. ISIT*, Jul. 2008, pp. 1218–1222.
- [10] N. Al-Falahy and O. Y. Alani, "Technologies for 5G networks: Challenges and opportunities," *IT Prof.*, vol. 19, no. 1, pp. 12–20, Jan./Feb. 2017.
- [11] S. Chen and J. Zhao, "The requirements, challenges, and technologies for 5G of terrestrial mobile telecommunication," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 36–43, May 2014.
- [12] J. Zhang, L. Dai, X. Li, Y. Liu, and L. Hanzo, "On low-resolution ADCs in practical 5G millimeter-wave massive MIMO systems," *IEEE Commun. Mag.*, vol. 56, no. 7, pp. 205–211, Jul. 2018.
- [13] B. Widrow and I. Kollár, *Quantization Noise: Roundoff Error in Digital Computation, Signal Processing, Control, and Communications*. Cambridge, U.K.: Cambridge Univ. Press, 2008, pp. 257–279.
- [14] J. Singh, *Communication Transceiver Design with Low-Precision Analog-to-Digital Conversion*. Santa Barbara, CA, USA: Univ. California, Santa Barbara, 2009.
- [15] J. J. Bussgang, "Crosscorrelation functions of amplitude-distorted Gaussian signals," Massachusetts Inst. Technol., Cambridge, MA, USA, RLE Tech. Rep. 216, 1952, pp. 14–30.
- [16] A. Gersho, R. Gray, and A. Gersho, *Vector Quantization and Signal Compression*, vol. 59, no. 1. Norwell, MA, USA: Springer, 1992, pp. 407–485.
- [17] D. Hui and D. L. Neuhoff, "Asymptotic analysis of optimal fixed-rate uniform scalar quantization," *IEEE Trans. Inf. Theory*, vol. 47, no. 3, pp. 957–977, Mar. 2001.
- [18] O. Dabeer, J. Singh, and U. Madhow, "On the limits of communication performance with one-bit analog-to-digital conversion," in *Proc. SPAWC*, 2006, pp. 1–5.
- [19] J. Singh, O. Dabeer, and U. Madhow, "On the limits of communication with low-precision analog-to-digital conversion at the receiver," *IEEE Trans. Commun.*, vol. 57, no. 12, pp. 3629–3639, Dec. 2008.
- [20] A. Mezghani and J. A. Nossek, "On ultra-wideband MIMO systems with 1-bit quantized outputs: Performance analysis and input optimization," in *Proc. ISIT*, Jun. 2007, pp. 1286–1289.
- [21] A. Mezghani and J. A. Nossek, "Analysis of Rayleigh-fading channels with 1-bit quantized output," in *Proc. ISIT*, Jul. 2008, pp. 260–264.
- [22] S. Krone and G. P. Fettweis, "Fading channels with 1-bit output quantization: Optimal modulation, ergodic capacity and outage probability," in *Proc. ITW*, Aug./Sep. 2010, pp. 1–5.
- [23] T. Koch and A. Lapidath, "Increased capacity per unit-cost by oversampling," in *Proc. IEEE 26th Conv. Elect. Electron. Eng. Isr.*, Nov. 2010, pp. 684–688.
- [24] S. Krone and G. P. Fettweis, "Capacity of communications channels with 1-bit quantization and oversampling at the receiver," in *Proc. SARNOF*, May 2012, pp. 1–7.
- [25] J. Mo and R. W. Heath, Jr., "High SNR capacity of millimeter wave MIMO systems with one-bit quantization," in *Proc. ITA*, Feb. 2014, pp. 1–5.
- [26] J. Mo and R. W. Heath, Jr., "Capacity analysis of one-bit quantized MIMO systems with transmitter channel state information," *IEEE Trans. Signal Process.*, vol. 63, no. 20, pp. 5498–5512, Oct. 2015.
- [27] S. Jacobsson, G. Durisi, M. Coldrey, U. Gustavsson, and C. Studer, "Throughput analysis of massive MIMO uplink with low-resolution ADCs," *IEEE Trans. Wireless Commun.*, vol. 16, no. 6, pp. 4038–4051, Jun. 2017.
- [28] K. Roth and J. A. Nossek, "MAC rate region of low resolution ADC digital and hybrid beamforming massive MIMO UL," in *Proc. ICC*, May 2017, pp. 1227–1232.
- [29] S. Rini, L. Barletta, Y. C. Eldar, and E. Erkip, "A general framework for low-resolution receivers for MIMO channels," 2017, *arXiv:1702.08133*. [Online]. Available: <https://arxiv.org/abs/1702.08133>
- [30] A. Khalili, S. Rini, L. Barletta, E. Erkip, and Y. C. Eldar, "On MIMO channel capacity with output quantization constraints," in *Proc. ISIT*, Jun. 2018, pp. 1355–1359.
- [31] P. Dong, H. Zhang, W. Xu, G. Y. Li, and X. You, "Performance analysis of multiuser massive MIMO with spatially correlated channels using low-precision ADC," *IEEE Commun. Lett.*, vol. 22, no. 1, pp. 205–208, Jan. 2018.
- [32] Q. Bai, A. Mezghani, and J. A. Nossek, "On the optimization of ADC resolution in multi-antenna systems," in *Proc. ISWCS*, Aug. 2013, pp. 1–5.
- [33] O. Orhan, E. Erkip, and S. Rangan, "Low power analog-to-digital conversion in millimeter wave systems: Impact of resolution and bandwidth on performance," in *Proc. ITA*, Feb. 2015, pp. 191–198.
- [34] J. Mo, A. Alkhateeb, S. Abu-Surra, and R. W. Heath, Jr., "Hybrid architectures with few-bit ADC receivers: Achievable rates and energy-rate tradeoffs," *IEEE Trans. Wireless Commun.*, vol. 16, no. 4, pp. 2274–2287, Apr. 2017.
- [35] L. Fan, S. Jin, C. K. Wen, and H. Zhang, "Uplink achievable rate for massive MIMO systems with low-resolution ADC," *IEEE Commun. Lett.*, vol. 19, no. 12, pp. 2186–2189, Oct. 2015.
- [36] J. Zhang, L. Dai, S. Sun, and Z. Wang, "On the spectral efficiency of massive MIMO systems with low-resolution ADCs," *IEEE Commun. Lett.*, vol. 20, no. 5, pp. 842–845, Feb. 2016.
- [37] K. Liu, C. Tao, L. Liu, T. Zhou, and Y. Liu, "Asymptotic analysis for low-resolution massive MIMO systems with MMSE receiver," *China Commun.*, vol. 15, no. 9, pp. 189–199, Sep. 2018.
- [38] N. Liang and W. Zhang, "Mixed-ADC massive MIMO uplink in frequency-selective channels," *IEEE Trans. Commun.*, vol. 64, no. 11, pp. 4652–4666, Nov. 2016.
- [39] W. Tan, S. Jin, C.-K. Wen, and Y. Jing, "Spectral efficiency of mixed-ADC receivers for massive MIMO systems," *IEEE Access*, vol. 4, pp. 7841–7846, 2016.
- [40] J. Zhang, L. Dai, Z. He, S. Jin, and X. Li, "Performance analysis of mixed-ADC massive MIMO systems over Rician fading channels," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 6, pp. 1327–1338, Jun. 2017.
- [41] J. Choi, B. L. Evans, and A. Gatherer, "ADC bit allocation under a power constraint for mmWave massive MIMO communication receivers," in *Proc. ICASSP*, Mar. 2017, pp. 3494–3498.
- [42] I. Z. Ahmed, H. Sadjadpour, and S. Yousefi, "A joint combiner and bit allocation design for massive MIMO using genetic algorithm," in *Proc. ACSSC*, Oct./Nov. 2017, pp. 1045–1049.
- [43] I. Z. Ahmed, H. Sadjadpour, and S. Yousefi, "Single-user mmWave massive MIMO: SVD-based ADC bit allocation and combiner design," 2018, *arXiv:1804.08595v1*. [Online]. Available: <https://arxiv.org/abs/1804.08595v1>
- [44] I. Z. Ahmed, H. R. Sadjadpour, and S. Yousefi, "Capacity analysis and bit allocation design for variable-resolution ADCs in Massive MIMO," in *Proc. MILCOM*, Oct. 2018, pp. 1–6.
- [45] I. Z. Ahmed, H. Sadjadpour, and S. Yousefi, "Optimal bit allocation variable-resolution ADC for massive MIMO," 2019, *arXiv:1902.03375*. [Online]. Available: <https://arxiv.org/abs/1902.03375>
- [46] J. M. Khoury, "On the design of constant settling time AGC circuits," *IEEE Trans. Circuits Syst. II, Analog Digit. Signal Process.*, vol. 45, no. 3, pp. 283–294, Mar. 1998.
- [47] J. E. Ohlson, "Exact dynamics of automatic gain control," *IEEE Trans. Commun.*, vol. COM-22, no. 1, pp. 72–75, Jan. 1974.

- [48] B. M. Murray and I. B. Collings, "AGC and quantization effects in a zero-forcing MIMO wireless system," in *Proc. VTC*, May 2006, pp. 1802–1806.
- [49] F. Sun, J. Singh, and U. Madhow, "Automatic gain control for ADC-limited communication," in *Proc. GLOBECOM*, Dec. 2010, pp. 1–5.
- [50] F. Sun, D. Liu, and G. Yue, "Particle filtering based automatic gain control for ADC-limited communication," in *Proc. VTC*, May 2011, pp. 1–5.
- [51] S. Feifei, "Study on key technologies of low-accuracy quantization in wireless receiver," Ph.D. dissertation, School Inf. Commun. Eng., Beijing Univ. Posts Telecommun., Beijing, China, 2011.
- [52] Y. Ye, J. Zhou, and J. Hu, "Automatic gain control scheme for M-PAM receiver with precision-limited ADC," in *Proc. ICCP*, Dec. 2014, pp. 1–4.
- [53] H. Sari, S. Moridi, L. Desperben, and P. Vandamme, "Baseband equalization and carrier recovery in digital radio systems," *IEEE Trans. Commun.*, vol. 35, no. 3, pp. 319–327, Mar. 1987.
- [54] H. Sari and S. Moridi, "New phase and frequency detectors for carrier recovery in PSK and QAM systems," *IEEE Trans. Commun.*, vol. COM-36, no. 9, pp. 1035–1043, Sep. 1988.
- [55] D. A. Sobel and R. W. Brodersen, "A 1 Gb/s mixed-signal baseband analog front-end for a 60 GHz wireless receiver," *IEEE J. Solid-State Circuits*, vol. 44, no. 4, pp. 1281–1289, Apr. 2009.
- [56] A. Host-Madsen and P. Handel, "Effects of sampling and quantization on single-tone frequency estimation," *IEEE Trans. Signal Process.*, vol. 48, no. 3, pp. 650–662, Mar. 2000.
- [57] T. Andersson, M. Skoglund, and P. Händel, "Frequency estimation by 1-bit quantization and table look-up processing," in *Proc. EUSIPCO*, Sep. 2000, pp. 1–4.
- [58] G. Zeitler, G. Kramer, and A. C. Singer, "Bayesian parameter estimation using single-bit dithered quantization," *IEEE Trans. Signal Process.*, vol. 60, no. 6, pp. 2713–2726, Jun. 2012.
- [59] S. Krone and G. Fettweis, "Achievable rate of single-carrier systems with optimal uniform quantization at the receiver," in *Proc. ITW*, Jan. 2010, pp. 1–5.
- [60] J. Singh and U. Madhow, "On block noncoherent communication with low-precision phase quantization at the receiver," in *Proc. ISIT*, Jun./Jul. 2009, pp. 2199–2203.
- [61] J. Singh and U. Madhow, "Phase-quantized block noncoherent communication," *IEEE Trans. Commun.*, vol. 61, no. 7, pp. 2828–2839, Jul. 2013.
- [62] Y. Fan, J. Chen, P. Cao, and C. Yu, "Performance of carrier phase estimation QPSK optical coherent receiver with N bit resolution ADCs," in *Proc. ICOCN*, Nov. 2014, pp. 1–4.
- [63] Z. Lin, X. Peng, and F. Chin, "Joint carrier frequency offset and channel estimation for OFDM based gigabit wireless communication system with low precision ADC," in *Proc. VTC*, Sep. 2011, pp. 1–5.
- [64] Z. Wang, H. Yin, and G. Wei, "Optimal monobit digital receiver for QPSK modulation with phase rotation," in *Proc. ICC*, Aug. 2013, pp. 525–530.
- [65] Z. Wang, H. Yin, W. Zhang, and G. Wei, "Monobit digital receivers for QPSK: Design, performance and impact of IQ imbalances," *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3292–3303, Aug. 2013.
- [66] A. Wadhwa and U. Madhow, "Blind phase/frequency synchronization with low-precision ADC: A Bayesian approach," in *Proc. ALLERTON*, Oct. 2013, pp. 181–188.
- [67] A. Wadhwa and U. Madhow, "Near-coherent QPSK performance with coarse phase quantization: A feedback-based architecture for joint phase/frequency synchronization and demodulation," *IEEE Trans. Signal Process.*, vol. 64, no. 17, pp. 4432–4443, Sep. 2016.
- [68] D. Li, X. Xiong, and H. Wang, "Performance analysis of CFO estimation for OFDM systems with low-precision quantization," in *Proc. LNEE*, 2015, pp. 1005–1016.
- [69] L. Jun, L. Zhongqiang, and X. Xingzhong, "Low-complexity synchronization scheme with low-resolution ADCs," *Information*, vol. 9, no. 12, pp. 313–326, 2018.
- [70] D. Zhu and R. W. Heath, Jr., "Directional timing synchronization in wideband millimeter wave cellular systems with low-resolution ADCs," in *Proc. ASILOMAR*, Oct./Nov. 2017, pp. 37–41.
- [71] D. Zhu, R. Bendlin, S. Akoum, A. Ghosh, and R. W. Heath, Jr., "Directional frame timing synchronization in wideband millimeter-wave systems with low-resolution ADCs," 2018, *arXiv:1809.02890*. [Online]. Available: <https://arxiv.org/abs/1809.02890>
- [72] F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, and F. Tufvesson, "Scaling up MIMO: Opportunities and challenges with very large arrays," *IEEE Signal Process. Mag.*, vol. 30, no. 1, pp. 40–60, Jan. 2013.
- [73] T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," *IEEE Trans. Wireless Commun.*, vol. 9, no. 11, pp. 3590–3600, Nov. 2010.
- [74] H. Yin, D. Gesbert, M. Filippou, and Y. Liu, "A coordinated approach to channel estimation in large-scale multiple-antenna systems," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 2, pp. 264–273, Mar. 2013.
- [75] R. R. Müller, L. Cottatellucci, and M. Vehkaperä, "Blind pilot decontamination," *IEEE J. Sel. Topics Signal Process.*, vol. 8, no. 5, pp. 773–786, Oct. 2014.
- [76] T. M. Lok and V. K.-W. Wei, "Channel estimation with quantized observations," in *Proc. ISIT*, Aug. 1998, p. 333.
- [77] M. T. Ivrla and J. A. Nossek, "On MIMO channel estimation with single-bit signal-quantization," in *Proc. ITG Workshop Smart Antennas*, 2007, pp. 1–7.
- [78] A. Mezghani, F. Antreich, and J. A. Nossek, "Multiple parameter estimation with quantized channel output," in *Proc. Int. ITG Workshop Smart Antennas*, Feb. 2010, pp. 143–150.
- [79] O. Dabeer and U. Madhow, "Channel estimation with low-precision analog-to-digital conversion," in *Proc. ICC*, May 2010, pp. 1–6.
- [80] P. Li, Z. Wang, and H. Yin, "Joint channel estimation and pre-equalization for monobit transmission system," in *Proc. ICC*, Aug. 2013, pp. 303–308.
- [81] A. Mezghani and J. A. Nossek, "Efficient reconstruction of sparse vectors from quantized observations," in *Proc. ITG Workshop Smart Antennas*, 2012, pp. 193–200.
- [82] J. Mo, P. Schniter, N. G. Prelcic, and R. W. Heath, Jr., "Channel estimation in millimeter wave MIMO systems with one-bit quantization," in *Proc. ASILOMAR*, Nov. 2014, pp. 957–961.
- [83] H. C. Papadopoulos, G. W. Wornell, and A. V. Oppenheim, "Sequential signal encoding from noisy measurements using quantizers with dynamic bias control," *IEEE Trans. Inf. Theory*, vol. 47, no. 3, pp. 978–1002, Mar. 2001.
- [84] O. Dabeer and A. Karnik, "Signal parameter estimation using 1-bit dithered quantization," *IEEE Trans. Inf. Theory*, vol. 52, no. 12, pp. 5389–5405, Dec. 2006.
- [85] O. Dabeer and E. Masry, "Multivariate signal parameter estimation under dependent noise from 1-bit dithered quantized data," *IEEE Trans. Inf. Theory*, vol. 54, no. 4, pp. 1637–1654, Apr. 2008.
- [86] J. Choi, D. J. Love, and D. R. Brown, "Channel estimation techniques for quantized distributed reception in MIMO systems," in *Proc. ASILOMAR*, Nov. 2014, pp. 1066–1070.
- [87] M. Masood, L. H. Afify, and T. Y. Al-Naffouri, "Efficient coordinated recovery of sparse channels in massive MIMO," *IEEE Trans. Signal Process.*, vol. 63, no. 1, pp. 104–118, Jan. 2015.
- [88] C. Stockle, J. Munir, A. Mezghani, and J. A. Nossek, "Channel estimation in massive MIMO systems using 1-bit quantization," in *Proc. SPAWC*, Jul. 2016, pp. 1–6.
- [89] J. Choi, J. Mo, and R. W. Heath, Jr., "Near maximum-likelihood detector and channel estimator for uplink multiuser massive MIMO systems with one-bit ADCs," *IEEE Trans. Commun.*, vol. 64, no. 5, pp. 2005–2018, Mar. 2016.
- [90] S. Jacobsson, G. Durisi, M. Coldrey, U. Gustavsson, and C. Studer, "One-bit massive MIMO: Channel estimation and high-order modulations," in *Proc. ICCW*, Jun. 2015, pp. 1304–1309.
- [91] C. Risi, D. Persson, and E. G. Larsson, "Massive MIMO with 1-bit ADC," 2014, *arXiv:1404.7736*. [Online]. Available: <https://arxiv.org/abs/1404.7736>
- [92] C. K. Wen, C. J. Wang, S. Jin, K. K. Wong, and P. Ting, "Bayes-optimal joint channel-and-data estimation for massive MIMO with low-precision ADCs," *IEEE Trans. Signal Process.*, vol. 64, no. 10, pp. 2541–2556, May 2016.
- [93] C. Mollén, J. Choi, E. G. Larsson, and R. W. Heath Jr., "Uplink performance of wideband massive MIMO with one-bit ADCs," *IEEE Trans. Wireless Commun.*, vol. 16, no. 1, pp. 87–100, Oct. 2016.
- [94] Y. Li, C. Tao, G. Seco-Granados, A. Mezghani, A. L. Swindlehurst, and L. Liu, "Channel estimation and performance analysis of one-bit massive MIMO systems," *IEEE Trans. Signal Process.*, vol. 65, no. 15, pp. 4075–4089, Aug. 2017.
- [95] C. Cao, H. Li, and Z. Hu, "An AMP based decoder for massive MU-MIMO-OFDM with low-resolution ADCs," in *Proc. ICNC*, Jan. 2017, pp. 449–453.
- [96] Z. Zhou, X. Chen, D. Guo, and M. L. Honig, "Sparse channel estimation for massive MIMO with 1-bit feedback per dimension," in *Proc. WCNC*, Mar. 2017, pp. 1–6.

- [97] S. Hussein, H. S. Hussein, and E. M. Mohamed, "Low complexity channel estimation technique for 1-bit ADC MIMO-constant envelope modulation using compressive sensing," in *Proc. APMC*, Nov. 2017, pp. 889–893.
- [98] S. Hussein, H. S. Hussein, and E. M. Mohamed, "Adaptive sparsity based channel estimator for 1-bit ADC MIMO-constant envelope modulation," in *Proc. BlackSeaCom*, 2018, pp. 1–5.
- [99] P. Sun, Z. Wang, R. W. Heath, Jr., and P. Schniter, "Joint channel-estimation/decoding with frequency-selective channels and few-bit ADCs," *IEEE Trans. Signal Process.*, vol. 67, no. 4, pp. 899–914, Feb. 2019.
- [100] J. T. Parker and P. Schniter, "Parametric bilinear generalized approximate message passing," *IEEE J. Sel. Topics Signal Process.*, vol. 10, no. 4, pp. 795–808, Jun. 2016.
- [101] P. Sun, Z. Wang, W. R. Heath, Jr., and P. Schniter, "Joint channel-estimation/decoding with frequency-selective channels and few-bit ADCs," in *Proc. 51st Asilomar Conf. Signals, Syst., Comput.*, Oct./Nov. 2017, pp. 1824–1828.
- [102] H. Kim and J. Choi, "Channel estimation for one-bit massive MIMO systems exploiting spatio-temporal correlations," in *Proc. GLOBECOM*, Dec. 2018, pp. 1–6.
- [103] C. Rusu, R. Mendez-Rial, N. Gonzalez-Prelcic, and Robert W. Heath, Jr., "Adaptive one-bit compressive sensing with application to low-precision receivers at mmWave," in *Proc. GLOBECOM*, Dec. 2014, pp. 1–6.
- [104] J. Rodríguez-Fernández, N. González-Prelcic, and R. W. Heath, Jr., "Channel estimation in mixed hybrid-low resolution MIMO architectures for mmWave communication," in *Proc. 50th Asilomar Conf. Signals, Syst. Comput.*, Nov. 2016, pp. 768–773.
- [105] J. Mo, P. Schniter, and R. W. Heath, Jr., "Channel estimation in broadband millimeter wave MIMO systems with few-bit ADCs," *IEEE Trans. Signal Process.*, vol. 66, no. 5, pp. 1141–1154, Mar. 2018.
- [106] J. Sung, J. Choi, and B. L. Evans, "Narrowband channel estimation for hybrid beamforming millimeter wave communication systems with one-bit quantization," in *Proc. ICASSP*, Apr. 2018, pp. 3914–3918.
- [107] A. Mezghani and A. L. Swindlehurst, "Blind estimation of sparse broadband massive MIMO channels with ideal and one-bit ADCs," *IEEE Trans. Signal Process.*, vol. 66, no. 11, pp. 2972–2983, Jun. 2018.
- [108] Y. Wang, W. Xu, H. Zhang, and X. You, "Wideband mmWave channel estimation for hybrid massive MIMO with low-precision ADCs," *IEEE Wireless Commun. Lett.*, vol. 8, no. 1, pp. 285–288, Feb. 2019.
- [109] F. Wang, J. Fang, H. Li, Z. Chen, and S. Li, "One-bit quantization design and channel estimation for massive MIMO systems," *IEEE Trans. Veh. Technol.*, vol. 67, no. 11, pp. 10921–10934, Nov. 2018.
- [110] M. S. Stein, S. Bar, J. A. Nossek, and J. Tabrikian, "Performance analysis for channel estimation with 1-bit ADC and unknown quantization threshold," *IEEE Trans. Signal Process.*, vol. 66, no. 10, pp. 2557–2571, May 2018.
- [111] Y. Rockah and P. Schultheiss, "Array shape calibration using sources in unknown locations—Part I: Far-field sources," *IEEE Trans. Acoust., Speech, Signal Process.*, vol. 35, no. 3, pp. 286–299, Mar. 1987.
- [112] I. Reuven and H. Messer, "A Barankin-type lower bound on the estimation error of a hybrid parameter vector," *IEEE Trans. Inf. Theory*, vol. 43, no. 3, pp. 1084–1093, May 1997.
- [113] H. Messer, "The hybrid cramer-rao lower bound—From practice to theory," in *Proc. 4th IEEE Workshop Sensor Array Multichannel Process.*, Jul. 2006, pp. 304–307.
- [114] Y. Noam and H. Messer, "Notes on the tightness of the hybrid Cramér–Rao lower bound," *IEEE Trans. Signal Process.*, vol. 57, no. 6, pp. 2074–2084, Jun. 2009.
- [115] C. Ren, J. Galy, E. Chaumette, P. Larzabal, and A. Renaux, "Hybrid Barankin–Weiss–Weinstein bounds," *IEEE Signal Process. Lett.*, vol. 22, no. 11, pp. 2064–2068, Nov. 2015.
- [116] N. J. Myers and R. W. Heath, Jr., "A compressive channel estimation technique robust to synchronization impairments," in *Proc. SPAWC*, Jul. 2017, pp. 1–5.
- [117] N. D. Sidiropoulos, L. De Lathauwer, X. Fu, K. Huang, E. E. Papalexakis, and C. Faloutsos, "Tensor decomposition for signal processing and machine learning," *IEEE Trans. Signal Process.*, vol. 65, no. 13, pp. 3551–3582, Jul. 2017.
- [118] N. J. Myers and R. W. Heath, Jr., "Joint CFO and channel estimation in millimeter wave systems with one-bit ADCs," in *Proc. CAMSAP*, Dec. 2017, pp. 1–5.
- [119] E. J. Candès, T. Strohmer, and V. Voroninski, "PhaseLift: Exact and stable signal recovery from magnitude measurements via convex programming," *Commun. Pure Appl. Math.*, vol. 66, no. 8, pp. 1241–1274, Aug. 2013.
- [120] N. J. Myers and R. W. Heath, Jr., "Message passing-based joint CFO and channel estimation in millimeter wave systems with one-bit ADCs," *arXiv:1803.09012*. [Online]. Available: <https://arxiv.org/abs/1803.09012>
- [121] G. Palumbo, "Understanding delta- sigma data converters," *IEEE Circuits Devices Mag.*, vol. 22, no. 4, pp. 31–32, Jul./Aug. 2006.
- [122] R. Blazquez, F. S. Lee, D. D. Wentzloff, P. P. Newaskar, J. D. Powell, and A. P. Chandrakasan, "Digital architecture for an ultra-wideband radio receiver," in *Proc. VTC*, 2003, vol. 2, no. 2, pp. 1303–1307.
- [123] S. Hoyos, B. M. Sadler, and G. R. Arce, "Monobit digital receivers for ultrawideband communications," *IEEE Trans. Wireless Commun.*, vol. 4, no. 4, pp. 1337–1344, Jul. 2005.
- [124] A. Mezghani, M. Rouatbi, and J. Nossek, "A modified MMSE receiver for quantized MIMO systems," in *Proc. ITGWorkshop Smart Antennas*, Feb. 2007, pp. 1–5.
- [125] K. Nakamura and T. Tanaka, "Performance analysis of signal detection using quantized received signals of linear vector channel," in *Proc. ISITA*, Dec. 2008, pp. 1–5.
- [126] L. Ke, H. Yin, W. Gong, and Z. Wang, "Finite-resolution digital receiver design for impulse radio ultra-wideband communication," *IEEE Trans. Wireless Commun.*, vol. 7, no. 12, pp. 5108–5117, Dec. 2008.
- [127] H. Yin, Z. Wang, L. Ke, and J. Wang, "Monobit digital receivers: Design, performance, and application to impulse radio," *IEEE Trans. Commun.*, vol. 58, no. 6, pp. 1695–1704, Jun. 2010.
- [128] A. Mezghani and J. A. Nossek, "Belief propagation based MIMO detection operating on quantized channel output," in *Proc. ISIT*, Jun. 2010, pp. 2113–2117.
- [129] A. Mezghani, M. Rouatbi, and J. A. Nossek, "An iterative receiver for quantized MIMO systems," in *Proc. MELECON*, Mar. 2012, pp. 1049–1052.
- [130] S. Wang, Y. Li, and J. Wang, "Convex optimization based multiuser detection for uplink large-scale MIMO under low-resolution quantization," in *Proc. ICC*, Jun. 2014, pp. 4789–4794.
- [131] S. Wang, Y. Li, and J. Wang, "Multiuser detection for uplink large-scale MIMO under one-bit quantization," in *Proc. ICC*, Jun. 2014, pp. 4460–4465.
- [132] S. Wang, Y. Li, and J. Wang, "Multiuser detection in massive MIMO with quantized phase-only measurements," in *Proc. ICC*, Jun. 2015, pp. 4576–4581.
- [133] S. Wang, Y. Li, and J. Wang, "Multiuser detection in massive spatial modulation MIMO with low-resolution ADCs," *IEEE Trans. Wireless Commun.*, vol. 14, no. 4, pp. 2156–2168, Apr. 2015.
- [134] C. Studer and G. Durisi, "Quantized massive MU-MIMO-OFDM uplink," *IEEE Trans. Commun.*, vol. 64, no. 6, pp. 2387–2399, Jun. 2016.
- [135] H. Wang, T. Liu, C.-K. Wen, and S. Jin, "Optimal data detection for OFDM system with low-resolution quantization," in *Proc. ICCS*, Dec. 2016, pp. 1–6.
- [136] H. Wang, C.-K. Wen, and S. Jin, "Bayesian optimal data detector for mmWave OFDM system with low-resolution ADC," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 9, pp. 1962–1979, Sep. 2017.
- [137] H. He, C.-K. Wen, and S. Jin, "Generalized expectation consistent signal recovery for nonlinear measurements," in *Proc. ISIT*, 2017, pp. 2333–2337.
- [138] H. He, C.-K. Wen, and S. Jin, "Bayesian optimal data detector for hybrid mmWave MIMO-OFDM systems with low-resolution ADCs," *IEEE J. Sel. Topics Signal Process.*, vol. 12, no. 3, pp. 469–483, Jun. 2018.
- [139] W. Zhang, "A general framework for transmission with transceiver distortion and some applications," *IEEE Trans. Commun.*, vol. 60, no. 2, pp. 384–399, Feb. 2012.
- [140] N. Liang and W. Zhang, "Mixed-ADC massive MIMO," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 983–997, Sep. 2016.
- [141] N. Liang and W. Zhang, "A mixed-ADC receiver architecture for massive MIMO systems," in *Proc. ITW*, Oct. 2015, pp. 229–233.
- [142] T. C. Zhang, C. K. Wen, S. Jin, and T. Jiang, "Mixed-ADC massive MIMO detectors: Performance analysis and design optimization," *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7738–7752, Sep. 2016.
- [143] S.-N. Hong and N. Lee, "Soft-output detector for uplink MU-MIMO systems with one-bit ADCs," *IEEE Commun. Lett.*, vol. 22, no. 5, pp. 930–933, May 2018.



- [144] Y.-S. Cho, S.-H. Kim, and S.-N. Hong, "Successive cancellation soft output detector for uplink MU-MIMO systems with one-bit ADCs," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2018, pp. 1–6.
- [145] S. Kim, N. Lee, and S.-N. Hong, "A low-complexity soft-output wMD decoding for uplink MIMO systems with one-bit ADCs," 2017, *arXiv:1707.02868*. [Online]. Available: <https://arxiv.org/abs/1707.02868>
- [146] D. Abdelhameed, H. S. Hussein, and E. M. Mohamed, "Affine linear transformation based sphere decoder for 1-bit ADC MIMO-constant envelope modulation," in *Proc. ICT*, May 2016, pp. 1–6.
- [147] D. Abdelhameed, H. S. Hussien, and E. M. Mohamed, "Adaptive sphere decoder for 1-bit ADC MIMO-constant envelope modulation detection," in *Proc. CCNC*, Jan. 2017, pp. 638–639.
- [148] H. S. Hussein, "Sparse MLD decoder for 1-bit ADC MIMO constant envelope modulation," in *Proc. BlackSeaCom*, Jun. 2018, pp. 1–5.
- [149] E. Björnson, M. Matthaiou, and M. Debbah, "Massive MIMO with non-ideal arbitrary arrays: Hardware scaling laws and circuit-aware design," *IEEE Trans. Wireless Commun.*, vol. 14, no. 8, pp. 4353–4368, Aug. 2015.
- [150] C. Studer, M. Wenk, and A. Burg, "MIMO transmission with residual transmit-RF impairments," in *Proc. Int. ITG Workshop Smart Antennas*, Feb. 2010, pp. 189–196.
- [151] E. Björnson, P. Zetterberg, M. Bengtsson, and B. Ottersten, "Capacity limits and multiplexing gains of MIMO channels with transceiver impairments," *IEEE Commun. Lett.*, vol. 17, no. 1, pp. 91–94, Jan. 2013.
- [152] X. Zhang, M. Matthaiou, E. Björnson, M. Coldrey, and M. Debbah, "On the MIMO capacity with residual transceiver hardware impairments," in *Proc. ICC*, Jun. 2014, pp. 5299–5305.
- [153] E. Björnson, J. Hoydis, M. Kountouris, and M. Debbah, "Massive MIMO systems with non-ideal hardware: Energy efficiency, estimation, and capacity limits," *IEEE Trans. Inf. Theory*, vol. 60, no. 11, pp. 7112–7139, Nov. 2014.
- [154] J. Zhang, L. Dai, X. Zhang, E. Björnson, and Z. Wang, "Achievable rate of Rician large-scale MIMO channels with transceiver hardware impairments," *IEEE Trans. Veh. Technol.*, vol. 65, no. 10, pp. 8800–8806, Oct. 2016.
- [155] X. Xia, D. Zhang, K. Xu, W. Ma, and Y. Xu, "Hardware impairments aware transceiver for full-duplex massive MIMO relaying," *IEEE Trans. Signal Process.*, vol. 63, no. 24, pp. 6565–6580, Dec. 2015.
- [156] Y. Liu, X. Xue, J. Zhang, X. Li, L. Dai, and S. Jin, "Multipair massive MIMO two-way full-duplex relay systems with hardware impairments," in *Proc. GLOBECOM*, Dec. 2017, pp. 1–6.
- [157] J. Zhang, Y. Wei, E. Björnson, Y. Han, and S. Jin, "Performance analysis and power control of cell-free massive MIMO systems with hardware impairments," *IEEE Access*, vol. 6, pp. 55302–55314, 2018.
- [158] D. W. Bliss, T. M. Hancock, and P. Schniter, "Hardware phenomenological effects on cochannel full-duplex MIMO relay performance," in *Proc. ASILOMAR*, Nov. 2012, pp. 34–39.
- [159] T. Riihonen, S. Werner, and R. Wichman, "Mitigation of loopback self-interference in full-duplex MIMO relays," *IEEE Trans. Signal Process.*, vol. 59, no. 12, pp. 5983–5993, Dec. 2011.
- [160] T. Riihonen, S. Werner, and R. Wichman, "Hybrid full-duplex/half-duplex relaying with transmit power adaptation," *IEEE Trans. Wireless Commun.*, vol. 10, no. 9, pp. 3074–3085, Sep. 2011.
- [161] T. Riihonen, S. Werner, and R. Wichman, "Transmit power optimization for multi-antenna decode-and-forward relays with loopback self-interference from full-duplex operation," in *Proc. ASILOMAR*, Nov. 2011, pp. 1408–1412.
- [162] H. A. Suraweera, I. Krikidis, and C. Yuen, "Antenna selection in the full-duplex multi-antenna relay channel," in *Proc. ICC*, Jun. 2013, pp. 4823–4828.
- [163] H. Q. Ngo, H. A. Suraweera, M. Matthaiou, and E. G. Larsson, "Multipair full-duplex relaying with massive arrays and linear processing," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 9, pp. 1721–1737, Sep. 2014.
- [164] R. H. Y. Louie, Y. Li, and B. Vucetic, "Practical physical layer network coding for two-way relay channels: Performance analysis and comparison," *IEEE Trans. Wireless Commun.*, vol. 9, no. 2, pp. 764–777, Feb. 2010.
- [165] P. Popovski and H. Yomo, "Wireless network coding by amplify-and-forward for bi-directional traffic flows," *IEEE Commun. Lett.*, vol. 11, no. 1, pp. 16–18, Jan. 2007.
- [166] L. Song, "Relay selection for two-way relaying with amplify-and-forward protocols," *IEEE Trans. Veh. Technol.*, vol. 60, no. 4, pp. 1954–1959, May 2011.
- [167] H. Cui, L. Song, and B. Jiao, "Multi-pair two-way amplify-and-forward relaying with very large number of relay antennas," *IEEE Trans. Wireless Commun.*, vol. 13, no. 5, pp. 2636–2645, May 2014.
- [168] G. Amarasuriya and H. V. Poor, "Multi-way amplify-and-forward relay networks with massive MIMO," in *Proc. PIMRC*, Sep. 2014, pp. 595–600.
- [169] S. Jin, X. Liang, K.-K. Wong, X. Gao, and Q. Zhu, "Ergodic rate analysis for multipair massive MIMO two-way relay networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 3, pp. 1480–1491, Mar. 2015.
- [170] G. Amarasuriya and H. V. Poor, "Multi-user relay networks with massive MIMO," in *Proc. ICC*, Jun. 2015, pp. 2017–2023.
- [171] X. Jia, M. Zhou, M. Xie, L. Yang, and H. Zhu, "Optimal design of secrecy massive MIMO amplify-and-forward relaying systems with double-resolution ADCs antenna array," *IEEE Access*, vol. 4, pp. 8757–8774, 2016.
- [172] J. Jiao, X. Jia, M. Zhou, M. Xie, and Q. Cao, "Full-duplex massive MIMO AF relaying system with low-resolution ADCs under ZFT/ZFR scheme," in *Proc. IAEAC*, Mar. 2017, pp. 2024–2028.
- [173] J. Liu, J. Xu, W. Xu, S. Jin, and X. Dong, "Multiuser massive MIMO relaying with mixed-ADC receiver," *IEEE Signal Process. Lett.*, vol. 24, no. 1, pp. 76–80, Dec. 2016.
- [174] P. Dong, H. Zhang, W. Xu, and X. You, "Efficient low-resolution ADC relaying for multiuser massive MIMO system," *IEEE Trans. Veh. Technol.*, vol. 66, no. 12, pp. 11039–11056, Dec. 2017.
- [175] C. Kong, C. Zhong, S. Jin, S. Yang, H. Lin, and Z. Zhang, "Full-duplex massive MIMO relaying systems with low-resolution ADCs," *IEEE Trans. Wireless Commun.*, vol. 16, no. 8, pp. 5033–5047, Aug. 2017.
- [176] Q. Cui, Y. Liu, Y. Liu, W. Xie, and Y. Zhao, "Multi-pair massive MIMO amplify-and-forward relaying system with low-resolution ADCs: Performance analysis and power control," *Sci. China Inf. Sci.*, vol. 61, no. 2, pp. 22311–22329, 2018.
- [177] C. Kong, A. Mezghani, C. Zhong, A. L. Swindlehurst, and Z. Zhang, "Multipair massive MIMO relaying systems with one-bit ADCs and DACs," *IEEE Trans. Signal Process.*, vol. 66, no. 11, pp. 2984–2997, Jun. 2018.
- [178] J. Zhang, L. Dai, Z. He, B. Ai, and O. A. Dobre, "Mixed-ADC/DAC multipair massive MIMO relaying systems: Performance analysis and power optimization," *IEEE Trans. Commun.*, vol. 67, no. 1, pp. 140–153, Jan. 2019.
- [179] M. Z. Win and R. A. Scholtz, "Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications," *IEEE Trans. Commun.*, vol. 48, no. 4, pp. 679–689, Apr. 2000.
- [180] R. T. Hoctor and H. Tomlinson, "Delay-hopped transmitted-reference RF communications," in *Proc. UWBST*, May 2002, pp. 265–269.
- [181] L. Yang and G. B. Giannakis, "Ultra-wideband communications: An idea whose time has come," *IEEE Signal Process. Mag.*, vol. 21, no. 6, pp. 26–54, Nov. 2004.
- [182] J. Tang, Z. Xu, and B. M. Sadler, "Performance analysis of B-bit digital receivers for TR-UWB systems with inter-pulse interference," *IEEE Trans. Wireless Commun.*, vol. 6, no. 2, pp. 494–505, Feb. 2007.
- [183] S. Hoyos, B. M. Sadler, and G. R. Arce, "Dithering and  $\Sigma\Delta$  modulation in mono-bit digital receivers for ultra-wideband communications," in *Proc. UWBST*, Nov. 2003, pp. 71–75.
- [184] E. Saberinia, A. H. Tewfik, K.-C. Chang, and G. E. Sobelman, "Analog to digital converter resolution of multi-band OFDM and pulsed-OFDM ultra wideband systems," in *Proc. ISCCSP*, Mar. 2004, pp. 787–790.
- [185] P. P. Newaskar, R. Blazquez, and A. P. Chandrakasan, "A/D precision requirements for digital ultra-wideband radio receivers," *J. VLSI Signal Process. Syst. Signal, Image Video Technol.*, vol. 39, no. 1, pp. 175–188, 2005.
- [186] W. Namgoong, "ADC and AGC requirements of a direct-sequence spread spectrum signal," in *Proc. MWSCAS*, Aug. 2001, pp. 744–747.
- [187] S. Franz and U. Mitra, "Quantized UWB transmitted reference systems," *IEEE Trans. Wireless Commun.*, vol. 6, no. 7, pp. 2540–2550, Jul. 2007.
- [188] W. Gong, H. Yin, L. Ke, and Q. Fu, "Performance analysis of IR-UWB 1-bit digital receivers," in *Proc. CISS*, Mar. 2009, pp. 897–901.
- [189] Q. Zhang, A. Nallanathan, and H. K. Garg, "Monobit digital Eigen-based receiver for transmitted-reference UWB communications," *IEEE Trans. Wireless Commun.*, vol. 8, no. 5, pp. 2312–2316, May 2009.
- [190] H. Khani, H. Nie, W. Xiang, Z. Xu, and Z. Chen, "Low complexity sub-optimal monobit receiver for transmitted-reference impulse radio UWB systems," in *Proc. GLOBECOM*, Dec. 2012, pp. 4084–4089.

- [191] H. Khani, H. Nie, W. Xiang, and Z. Chen, "Inter-Symbol interference cancelation in monobit transmitted-reference impulse radio UWB receivers," in *Proc. WCNC*, Apr. 2013, pp. 2585–2590.
- [192] H. Khani, H. Nie, W. Xiang, Z. Xu, and Z. Chen, "Polarity-invariant square law technology for monobit impulse radio ultra wideband receivers," *IEEE Trans. Veh. Technol.*, vol. 63, no. 1, pp. 458–464, Jan. 2014.
- [193] H. Khani, H. Nie, W. Xiang, Z. Xu, S. Addepalli, and Z. Chen, "Polarity-invariant square law technology for transmitted reference UWB receivers digitizing with a monobit ADC," in *Proc. ICC*, Jun. 2012, pp. 4520–4524.
- [194] H. Khani, "Iterative algorithms to compensate for quantization noise in monobit transmitted-reference receivers," in *Proc. ICUBW*, Sep. 2014, pp. 30–35.
- [195] W. H. Chin, Z. Fan, and R. Haines, "Emerging technologies and research challenges for 5G wireless networks," *IEEE Wireless Commun.*, vol. 21, no. 2, pp. 106–112, Apr. 2014.
- [196] S. Wang, Y. Xin, S. Chen, W. Zhang, and C. Wang, "Enhancing spectral efficiency for lte-advanced and beyond cellular networks [guest editorial]," *IEEE Wireless Commun.*, vol. 21, no. 2, pp. 8–9, Apr. 2014.
- [197] C. Shepard, H. Yu, N. Anand, E. Li, T. Marzetta, R. Yang, and L. Zhong, "Argos: Practical many-antenna base stations," in *Proc. MOBICOM*, 2012, pp. 53–64.
- [198] C. Shepard, H. Yu, and L. Zhong, "ArgosV2: A flexible many-antenna research platform," in *Proc. MobiCom*, 2013, pp. 163–166.
- [199] J. Vieira, S. Malkowsky, K. Nieman, Z. Mierni, N. Kundargi, L. Liu, I. Wong, V. Öwall, O. Edfors, and F. Tufvesson, "A flexible 100-antenna testbed for Massive MIMO," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2014, pp. 287–293.
- [200] X. Yang, W. Lu, N. Wang, K. Nieman, C.-K. Wen, C. Zhang, S. Jin, X. Mu, I. Wong, Y. Huang, and X. You, "Design and implementation of a TDD-based 128-antenna massive MIMO prototype system," *China Commun.*, vol. 14, no. 12, pp. 162–187, 2017.
- [201] F. Boccardi, R. W. Heath, Jr., A. Lozano, T. L. Marzetta, and P. Popovski, "Five disruptive technology directions for 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 74–80, Feb. 2014.
- [202] S. A. Busari, K. M. S. Huq, S. Mumtaz, L. Dai, and J. Rodriguez, "Millimeter-wave massive MIMO communication for future wireless systems: A survey," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 2, pp. 836–869, 2nd Quart., 2018.
- [203] H.-K. Lee, D. M. Kim, Y. Hwang, S. M. Yu, and S.-L. Kim, "Feasibility of cognitive machine-to-machine communication using cellular bands," *IEEE Wireless Commun.*, vol. 20, no. 2, pp. 97–103, Apr. 2013.
- [204] S.-Y. Lien, K.-C. Chen, and Y. Lin, "Toward ubiquitous massive accesses in 3GPP machine-to-machine communications," *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 66–74, Apr. 2011.
- [205] F. Sotrobiani and W. Yu, "Hybrid beamforming with finite-resolution phase shifters for large-scale MIMO systems," in *Proc. SPAWC*, Jun./Jul. 2015, pp. 136–140.
- [206] J. Mo, A. Alkhateeb, S. Abu-Surra, and R. W. Heath, Jr., "Achievable rates of hybrid architectures with few-bit ADC receivers," in *Proc. ITG Workshop Smart Antennas*, Mar. 2016, pp. 1–8.
- [207] L.-F. Lin, W.-H. Chung, H.-J. Chen, and T.-S. Lee, "Energy efficient hybrid precoding for multi-user massive MIMO systems using low-resolution ADCs," in *Proc. SiPS*, Oct. 2016, pp. 115–120.
- [208] W. B. Abbas, F. Gomez-Cuba, and M. Zorzi, "Millimeter wave receiver efficiency: A comprehensive comparison of beamforming schemes with low resolution ADCs," *IEEE Trans. Wireless Commun.*, vol. 16, no. 12, pp. 8131–8146, Dec. 2017.
- [209] K. Roth and J. A. Nossek, "Achievable rate and energy efficiency of hybrid and digital beamforming receivers with low resolution ADC," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 9, pp. 2056–2068, Sep. 2017.
- [210] K. Roth and J. A. Nossek, "Robust massive MIMO equalization for mmWave systems with low resolution ADCs," in *Proc. WCNC*, Apr. 2018, pp. 113–118.
- [211] K. Roth, H. Pirzadeh, and A. L. Swindlehurst, and J. A. Nossek, "A comparison of hybrid beamforming and digital beamforming with low-resolution ADCs for multiple users and imperfect CSI," *IEEE J. Sel. Topics Signal Process.*, vol. 12, no. 3, pp. 484–498, Jun. 2018.
- [212] J. Choi, B. L. Evans, and A. Gatherer, "Resolution-adaptive hybrid MIMO architectures for millimeter wave communications," *IEEE Trans. Signal Process.*, vol. 65, no. 23, pp. 6201–6216, Dec. 2017.
- [213] J. Choi, G. Lee, and B. L. Evans, "Two-stage analog combining in hybrid beamforming systems with low-resolution ADCs," *IEEE Trans. Signal Process.*, vol. 67, no. 9, pp. 2410–2425, May 2019.
- [214] J. Yang, X. Yang, S. Jin, C.-K. Wen, and M. Matthaiou, "A low-resolution ADC module assisted hybrid beamforming architecture for mmWave communications," 2018, *arXiv:1803.09515*. [Online]. Available: <https://arxiv.org/abs/1803.09515>
- [215] J. Choi, G. Lee, and B. L. Evans, "User scheduling for millimeter wave hybrid beamforming systems with low-resolution ADCs," *IEEE Trans. Wireless Commun.*, vol. 18, no. 4, pp. 2401–2414, Apr. 2019.
- [216] J. Choi and B. L. Evans, "User scheduling for millimeter wave MIMO communications with low-resolution ADCs," in *Proc. ICC*, May 2018, pp. 1–6.
- [217] J. Wang, Z. Lan, C.-W. Pyo, T. Baykas, C.-S. Sum, M. A. Rahman, J. Gao, R. Funada, F. Kojima, H. Harada, and S. Kato, "Beam codebook based beamforming protocol for multi-Gbps millimeter-wave WPAN systems," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 8, pp. 1390–1399, Oct. 2009.
- [218] A. Alkhateeb, J. Mo, N. Gonzalez-Prelcic, and R. W. Heath, Jr., "MIMO precoding and combining solutions for millimeter-wave systems," *IEEE Commun. Mag.*, vol. 52, no. 12, pp. 122–131, Dec. 2014.
- [219] B. Murmann, *ADC Performance Survey 1997–2013*. Accessed: Dec. 7, 2018. [Online]. Available: <https://web.stanford.edu/murmann/adcsurvey.html>
- [220] Q. Bai and J. A. Nossek, "Energy efficiency maximization for 5G multi-antenna receivers," *Trans. Emerg. Telecomm. Technol.*, vol. 26, no. 1, pp. 3–14, 2015.
- [221] T. E. Bogale and L. B. Le, "Massive MIMO and millimeter wave for 5G wireless HetNet: Potentials and challenges," 2015, *arXiv:1510.06359*. [Online]. Available: <https://arxiv.org/abs/1510.06359>



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