# Wireless Beam Modulation: An Energy- and Spectrum-Efficient Communication Technology for Future Massive IoT Systems

Jienan Chen, Shuai Li, Jiyun Tao, Shengli Fu, and Gerald E. Sobelman


## Abstract

The potential of a system combining millimeter-wave (mmWave) communication and multiple-input multiple-output (MIMO) technology has motivated an extensive effort in both the research community and industry. With the much higher spectrum band, mmWave is considered to be a promising technology to solve the congestion problem in the sub-6 GHz band for future massive Internet of Things (IoT) systems. However, mmWave is still a long way from being a practical implementation for an IoT terminal due to high hardware cost and energy consumption. In this article, we introduce a new mmWave transmission technology called wireless beam modulation (WBM). The distinguishing feature of WBM is that bit information is transmitted through the propagation attenuation differences of signal beams instead of being carried by the original signal beam. While maintaining the high data transmission capability of mmWave frequencies, this change brings the advantage of high energy efficiency and low-cost mmWave hardware implementation to the IoT node. It can be deployed without shifter array and complex signal processing, such as precoding or even channel estimation. The basic idea of WBM is based on the recently proposed over-the-air modulation (OTAM) method but with several significant improvements. By formulating multiple beams at the access point (AP) node, WBM enables multiple-user access with spatial-division multiplexing, which significantly improves the spectrum efficiency compared to OTAM. Moreover, by aligning multiple beams between the IoT nodes and the central AP, WBM provides robust transmission and allows higher-order modulation. Hence, the proposed WBM achieves a good balance between high data transmission and spectrum efficiency with low hardware cost, which is promising for upcoming mmWave massive IoT systems.


## Introduction

The total number of Internet of Things (IoT) devices is projected to be in the range of 75 billion worldwide by 2025, an increase by a factor of five in the last decade [1]. With the exponential growth of IoT devices, it is believed that developing a scalable, energy-efficient, and reliable IoT connectivity solution can bring enormous benefits to society and industries. Unfortunately, the enormous increase of IoT devices brings a great challenge for future wireless communication systems, especially when broadband IoT services are required. Broadband IoT connectivity is supposed to provide superior performance in terms of high throughput and low latency, such as for providing connectivity to tens of billions of cameras. Therefore, the massive connections of IoT devices with broadband data communication will place enormous pressure on the already congested low-band-based (sub-6 GHz) WiFi and cellular bands. Also, omnidirectional-antenna-based IoT sensors have low transmission efficiency, which is counter to the IoT system's low power requirement.

The latest millimeter wave (mmWave) technology provides a new vision for future massive and broadband connectivity IoT systems. By using multi-gigahertz of unlicensed bandwidth, mmWave transmission technology provides much higher bandwidth resources than existing WiFi and cellular networks. It has great potential for enabling future massively connected broadband IoT devices. However, due to the high power consumption, the prevailing viewpoint of current researchers is that mmWave is not suited for this application. According to a report, the current mmWave platforms consume about 20 W for each radio frequency (RF) chain because of the high power consumption of RF components operating at mmWave frequencies [2]. Besides that, the mmWave communication system requires a large-scale antenna array to implement beamforming, which is critical to compensation for the propagation attenuation of the high-frequency wave transmission [3]. A phase shifter with an amplifier is connected to each antenna. A power amplifier is added with the phase shifter to compensate for the phase shifter's insertion loss. Hence, the energy cost is increased rapidly with a large number of phase shifter arrays. The power consumption increases significantly with the antenna scale, which is impractical for the deployment of IoT devices [4]. Moreover, the expensive hardware cost also limits its wide application in IoT devices [5]. It is reported that the current full mmWave radio cost (including the phase shifter array,

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mixer, and amplifiers) is on the order of hundreds of dollars, far more than a typical WiFi module and more than the camera sensor itself.

Recently, an over-the-air modulation (OTAM) technology has been proposed to offer a simple and low-power architecture for IoT applications [6]. The main idea of OTAM is to integrate beam selection and data modulation. Thus, by exploiting the high attenuation property and the directionality requirement of mmWave communication, it creates amplitude shift key (ASK) modulation. On the IoT node side, it creates two beams with two fixed directions to transmit a bit 0 or 1. On the access point (AP) side, an omnidirectional antenna is deployed, where the transmitting information can be recovered from the two groups of signals with different attenuation received by the AP. The working principle of OTAM is detailed in the next section. Compared to the existing mmWave system, OTAM offers two benefits: first, the phase shifter array with an amplifier for each antenna is unnecessary, which saves both energy consumption and the cost of the hardware. Second, beam alignment and channel estimation processes are also unnecessary for OTAM, which avoids complex digital signal processing. The implementation results indicate that an OTAM-based mmWave system has a lower hardware cost than existing mmWave systems. Compared to a sub-6 GHz system, OTAM supplies much higher bandwidth and energy efficiency. However, OTAM still has several challenges:

- Multiple-node access with spatial-division multiplexing (SDM). When multiple nodes access the AP simultaneously, the signals from each node appear as strong inference with each other on the AP's omnidirectional antenna, which will degrade the performance.
- Low spectrum efficiency. This problem is directly related to the previous one. When SDM is unavailable, only frequency-division multiplexing (FDM) or time-division multiplexing (TDM) can support multi-stream or multi-node access, which leads to low spectrum efficiency.
- Mobility connection problem. OTAM assumes that the position of a sensor node is static, where only a dynamic environment is considered, such as blocking the line-of-sight (LoS) path between the IoT nodes and the AP due to object movement.

The above challenges can significantly limit the application of OTAM in a practical massively connected IoT system.

From bottleneck to breakthrough, the wireless beam modulation (WBM) method is introduced in this article. In the WBM scheme, instead of using an omnidirectional antenna, the AP applies a hybrid beamforming architecture and generates multiple beams through multiple groups of antennas with phase shifters to align multiple IoT nodes. Also, the IoT nodes stay unchanged. To this end, SDM can be achieved by isolating the signals from multiple IoT nodes in different beam directions. The main advantage of WBM is supporting multiple users or multiple streams access with a spatial dimension, which leads to higher spectrum efficiency. Besides, beam tracking technology can be employed to solve the mobility problem of OTAM [7]. Although the hybrid beamforming array is required at the AP sides in the WBM system, one AP can serve multiple IoT nodes, and the cost and power can be amortized over a large number of IoT nodes. Compared to the existing mmWave system, the hardware cost for WBM is also relatively low without complex signal processing, such as channel estimation and precoding. Thus, WBM exhibits high data transmission bandwidth, spectrum efficiency, and energy efficiency with relatively low hardware cost and power consumption.

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## Principle of Wireless Beam Modulation

Data transmission in the WBM system is achieved by using the difference in signal propagation attenuation based on the OTAM technology but with significant improvement on the AP side. By replacing the omnidirectional antenna with a hybrid beamforming structure at the AP, WBM overcomes the limitations in multiple-user access, increases the robustness of data transmission, and provides downlink communication capability. The following subsection introduces the basic principle of modulation OTAM and presents a detailed system of WBM.

### Over-the-Air Modulation

The principle of the OTAM scheme is simple and straightforward. Utilizing the propagation attenuation characteristics of different beams over the air to transmit bit sequences can be considered a type of binary ASK modulation. Therefore, the traditional ASK demodulation principle can be applied to the OTAM system. Specifically, the node in OTAM contains two patch antennas that can generate two beams with different fixed directions. Different antenna arrays are turned on, enabled according to the information bits to be transmitted. Due to the different directions of the beams, signals transmitted by different beams will experience different paths with different attenuation characteristics when propagating in the channel, which makes the received signal significantly different in amplitude. Based on the differences, the information bits can be decoded by detecting the amplitude of the signal, as in ASK demodulation.

The significant advantage of OTAM is the realization of mmWave transmission with a relatively simple hardware scheme and using ASK signal processing techniques. Remarkably, OTAM can perform spectrum reuse in space by using directional antennas. Compared to a traditional ASK modulation system, OTAM offers higher spectrum efficiency and data transmission rates. At the same time, it has a more straightforward and lower-power architecture than existing mmWave systems.

However, there are several limitations with OTAM, namely poor transmission performance when there is equal path loss, weak support for multiple-node access in SDM, handling a mobile node scenario, and lack of downlink transmission capability. If the path attenuation corresponding to the two beams is similar, the information bits are difficult to distinguish and recover by detecting the amplitude of received signal, which leads to poor transmission performance. Although frequency shift keying (FSK) is considered to help decode the information in that case, it is still poor when the channel attenuation is high for both

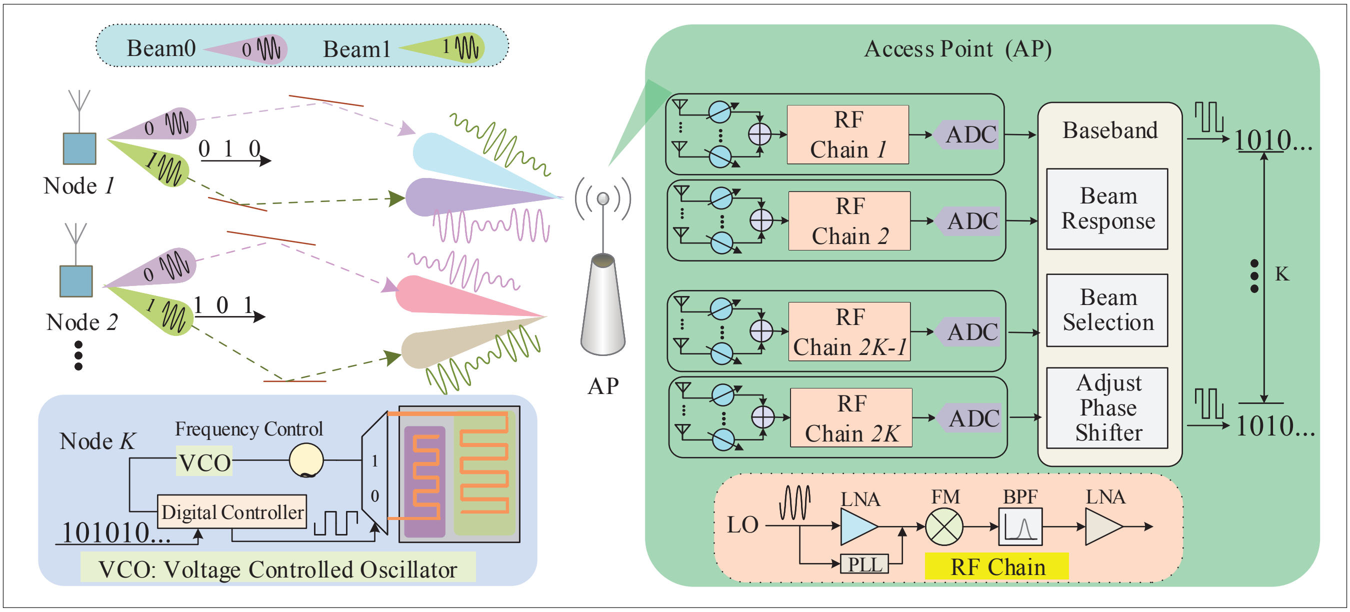


**FIGURE 1.** The system scheme of wireless beam modulation (WBM). An information bit is transmitted using the attenuation of a channel. The IoT node is implemented with a simple hardware scheme. The AP is based on a hybrid beamforming structure to support multiple-node access.

streams. Moreover, when multiple nodes access the AP simultaneously, the signals from each node appear as strong inference with each other on the AP's omnidirectional antenna, which will degrade the performance. Finally, IoT node movement and downlink data transmission are challenging to support in OTAM since the AP is unable to generate specific beams for each IoT node.

## Wireless Beam Modulation

To solve the above problems, we propose the WBM scheme. The critical improvement made by the WBM scheme is to use a hybrid antenna array to replace the omnidirectional antenna of the AP in the OTAM scheme. In this way, WBM can create multiple beams with specific directions to align the various IoT nodes. As a result, WBM can support multiple-node access with SDM, which can improve the spectrum efficiency significantly. Furthermore, it enables beam tracking for robust connections by controlling the beam direction.

As shown in Fig. 1, the IoT node consists of a voltage-controlled oscillator (VCO), an antenna switcher, and two groups of microstrip antennas. These two groups of antennas can generate two beams in different directions, called Beam0 and Beam1. Since the direction of the beam is fixed, the expensive phase shifter array can be replaced by carefully designed microstrip antennas [8]. The different direction beams are formulated by utilizing the line length difference of microstrip antennas. For the WBM-based IoT node, only a VCO device is required to generate a sine wave signal for transmission. Hence, the overall power consumption of the IoT node is relatively low.

On the other side, the AP consists of analog beamforming arrays, RF chains, and a baseband processor, as shown in Fig. 1. As shown in [8], the beamforming arrays are based on a sub-connected structure, where each phase shifter and amplifier pair are connected to each antenna, and multiple antennas are combined into one RF chain as a group. For each node, the AP uses two group antennas to generate two beams to align the Beam0 and Beam1 of the node. Since the transmitted ASK signal has a simple modulated form, the RF chains of the AP can be implemented with low-power and low-cost hardware. For instance, the filter is implemented by a microstrip coupled line filter on the printed circuit board (PCB) without costly components, and a sub-harmonic mixer implements the local oscillator (LO). Hence, the multiple RF chains at the AP will not pose much extra burden compared to the original OTAM method.

The baseband processor consists of three modules: beam searching and alignment, signal detection and decoding, and beam tracking. In the signal detection and decoding processing module, the signals received by the two groups of antennas are aligned with Beam0 and Beam1 of the specified node and can be demodulated jointly. After the beam alignment process is finished, WBM estimates the receiving energy from the Beam0 array and Beam1 array, respectively. The transmitted bit is decoded by calculating the difference between the two received energies. Unlike OTAM with only an omnidirectional antenna, the proposed WBM system employs two groups of receiving antennas for each IoT node. The beam direction of each antenna array is aligned with the two bit streams, respectively. At the AP side, the bit is decoded with the path loss difference and the propagation direction difference. Hence, even when the two transmit signals experience the same propagation loss, WBM can distinguish them with two receiving antenna arrays.

The beam searching and alignment process controls the phase shifter array to search the angle of arrival (AoA) of Beam1 or Beam0 for each node. We assume the movement between the IoT node and AP is smooth, such as security camera and sensoring camera in an autonomous system [8]. When the mobility of the IoT nodes is relatively slow, we propose an iterative beam

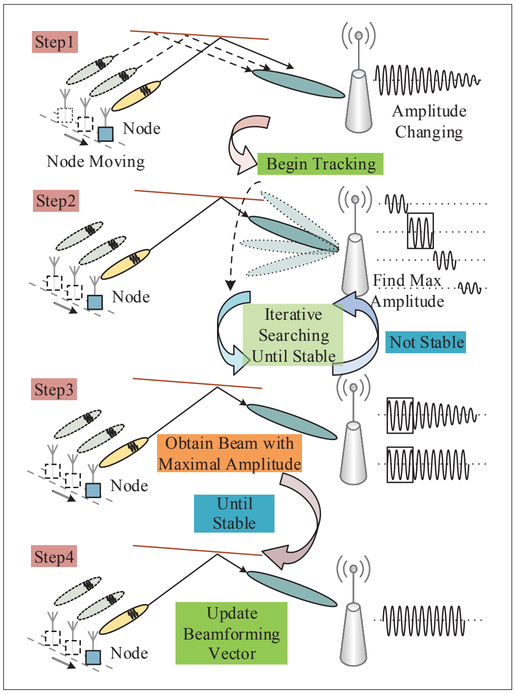


**FIGURE 2.** The beam tracking process based on an iterative searching process.

searching method to achieve beam searching and alignment. The vectors of the discrete Fourier transform (DFT) matrix are not only mutually orthogonal but also mathematically close to the response vector of the antenna array. In this design, we employ a DFT matrix as a beamforming codebook [9], where each row (or column) of the DFT matrix can represent a specific beam direction. Since only the AP requires the beam searching process, the searching complexity is reduced from $O(n^2)$ to $O(n)$ without the feedback from the IoT node, where $n$ represents the size of the DFT codebook. Furthermore, by using the fast alignment technology proposed in [10], the beam alignment can be completed in milliseconds. In the beam searching process, the beam corresponding to the highest received signal amplitude is aligned with the specified node. By using the multiple sub-connected phase shifter arrays with multiple RF chains, WBM can formulate multiple independent directional beams to align with different IoT nodes, which solves the problem of multiple user access and improves spectrum efficiency.

However, the drawback of this method is that if the LoS path is blocked, the beam is not aligned with the specified node, which leads to poor system performance. In this article, we propose a bit-level multiple-beam alignment method to improve detection performance. The basic principle is creating two parallel beams to align with Beam0 and Beam1, described in the next section.

In the beam tracking module, we employ an iterative beam search method to predict and track the nodes of low-speed movement in the simple IoT application scenarios. As shown in Fig. 2, the beam tracking based on the proposed method can be divided into four steps. First, in step 1, when the amplitude of the received signal has a large variation, we assume that the position of the IoT node has changed or the signal propagation path is blocked. Then, in step 2, WBM controls the analog shifter array to search nearby angles and find the one with maximal amplitude. In step 3, the angle setting of the analog shifter array is updated by the one with maximal amplitude. After that, in step 4, we repeat steps 2 and 3 until the maximal beam angle is obtained or the amplitude of the received signal becomes stable. The stable state is determined by the variance of received signal energy over a period of time. If the variance is below a given threshold, we consider the search process to be stable. Since the beam alignment applied in WBM can be completed in milliseconds, the channel can be considered stable during the beam alignment process. Consequently, the whole beam searching and alignment process can be completed in a short time.

If the AP receives multiple transmitting beams, WBM employs multiple RF chains to align different IoT nodes. Hence, WBM for each RF chain can recover the aligned IoT node signal with high received energy and consider other low received energy beams as interference. To solve the interference from other IoT nodes, we can employ successive interference cancellation (SIC) method to reduce the signal interference. The basic idea of SIC is to successively subtract the interference from the previously detected IoT node whose received signal has higher quality, where the interference is estimated from the reference signal of each user. The beam allocation strategy can also be applied to schedule the time or frequency resource for IoT nodes to support access by multiple IoT nodes, which combines SDM with time-division multiplexing (TDM) or frequency-division multiplexing (FDM).

The beam direction of each antenna array is aligned with the two bit streams, respectively. At the receiving end, the bit is decoded with the path loss difference and the propagation direction difference. Hence, even when the two transmit signals experience the same propagation loss, WBM can distinguish them with two receiving antenna arrays.

## Physical Layer Access and Optimization

In this section, we present additional details of WBM, specifically IoT node access in the physical layer and optimization.

### Physical Layer Access

The network stack design for WBM is closely related to the operational scheme and the transmission properties. As shown in Fig. 3, the packet is mainly composed of a functional segment (FS), Header, Data, and a cyclic redundancy code (CRC). The FS is used for beam searching and alignment, which mainly includes the Beam1 sequence and Beam0 training sequence with a duration of 0.5 ms and guard period (GP) with a duration of 0.1 ms. Moreover, the GP is set to avoid confusion between the Beam0 sequence and the Beam1 sequence. In this work, we employ a fast multiple-beam-based alignment method proposed in [10]. By hashing the spatial directions into different bins, the beam alignment process can be completed in milliseconds instead of exhaustively searching the entire space. Hence, at the beginning of the IoT node access procedure, the IoT node first transmits a Beam0 signal with a fixed direction. After the AP has detected the new transmitted beam signal, it begins the multiple-beam alignment process and sets the phase shifter array to aim to the beam direction having maximal amplitude. The same process is performed again for Beam1, and then back for Beam0 to ensure that the maximal amplitude is

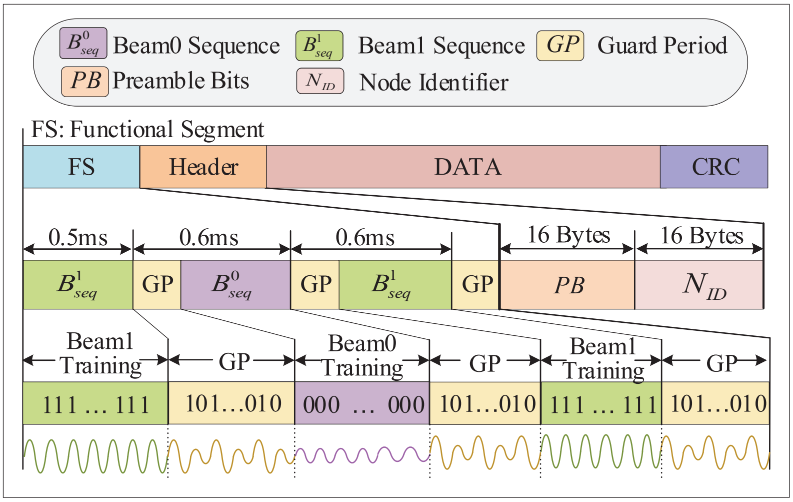


FIGURE 3. The packet information for IoT node access in WBM. The beam training is only needed for the initial IoT node access. A bit is transmitted by selecting a corresponding antenna array.

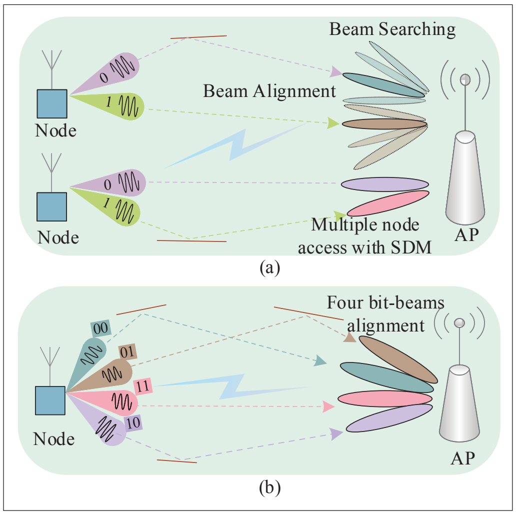


FIGURE 4. The multiple bit-beam alignment technology for supporting a reliable and higher-order modulation system.

obtained. We select the direction with the larger amplitude between Beam0 and Beam1 as the phase shifter array direction of the AP. The training packet in Beam1 is also used for the synchronization. To avoid the misalignment of Beam1, we transmit the Beam1 training packet again after the Beam0 training packet. After the beam alignment process has finished, the communication uplink is established between the IoT node and the AP. Then a 16-byte-length preamble known at both the IoT node and the AP is employed to distinguish the bits represented by different beams to facilitate the decoding of the Data part in the frame. Following the preamble, an 8-byte node identity document (ID) is used as a tag for each IoT node. Finally, the CRC is employed to check the correctness of the whole frame.

## Optimization by Multiple Bit-Beam Alignment

The difficulties in using only one beam for each IoT node are twofold: the downlink is challenging to establish, and the transmission performance is poor if the channel attenuation of both of the alignment beams is high. The same problem also exists in the original OTAM. To solve this problem, we propose a bit-level multiple-alignment method. As shown in Fig. 4a, the AP employs two separate phase shifter arrays to generate two beams for transmitting bit 0 and bit 1. To achieve this, we need a slight modification in the hardware structure and IoT node access process. For the hardware structure, we need to divide the original antenna group into two groups for each IoT node to align with Beam0 and Beam1.

In the accessing process, the AP performs the beam searching process separately and finds two maximal amplitude beam directions for Beam0 and Beam1. Instead of assigning only one maximal beam direction, the AP assigns two maximal amplitude beam directions (i.e., for bit 1 and bit 0 transmissions). The proposed alignment method solves the problem of one beam alignment presented in the original OTAM. First, it enables the downlink transmission by setting the corresponding phase shifter array. For instance, to transmit bit 1, the AP selects the aligned phase shifter and an antenna array of Beam1 to transmit a sine wave. Then, at the IoT node, the phase shifter array for Beam1 will receive a high amplitude signal, whereas Beam0 will receive a low amplitude signal because of the different beam alignment schemes. The transmitted information can be detected and decoded by an ASK demodulator, which completes the downlink data transmission. Second, by using multiple-bit-beam alignments, the communication performance will not be degraded by the existence of an LoS channel link between the IoT node and the AP, which is more robust than in the original OTAM. The reason is that the bit transmission of multiple bit-beam alignments depends not only on the channel attenuation difference between Beam0 and Beam1 but also on the beam direction. Even if there is no LoS channel link between the IoT node and the AP, the bit 0 and bit 1 transmission still exhibits quite different receiving amplitudes at the AP beam array due to the beam alignment. Hence, the proposed method shows better communication performance with no LoS channel link scenario. Lastly, by using multiple bit-beam alignment technology, we can extend the binary modulation-based WBM to a high-order modulation system, which can further improve the spectrum efficiency. As shown in Fig. 4b, at the IoT node, it generates four different direction beam signals to represent 00, 01, 10, and 11. At the AP side, four antenna and phase shifter array groups are employed to align the four transmission beams. Hence, transmission efficiency is improved by a factor of two with the multiple bit-beam alignment methodology. Theoretically, the modulation order can be further improved by using additional beams but is limited in practice by hardware constraints in supporting more antenna and phase shifter array groups. It is also limited by the number of available transmission paths between the AP and IoT nodes.

## Performance Analysis

In this section, we simulate and analyze the performance of WBM in terms of bit error rate (BER), spectrum efficiency, and hardware efficiency.

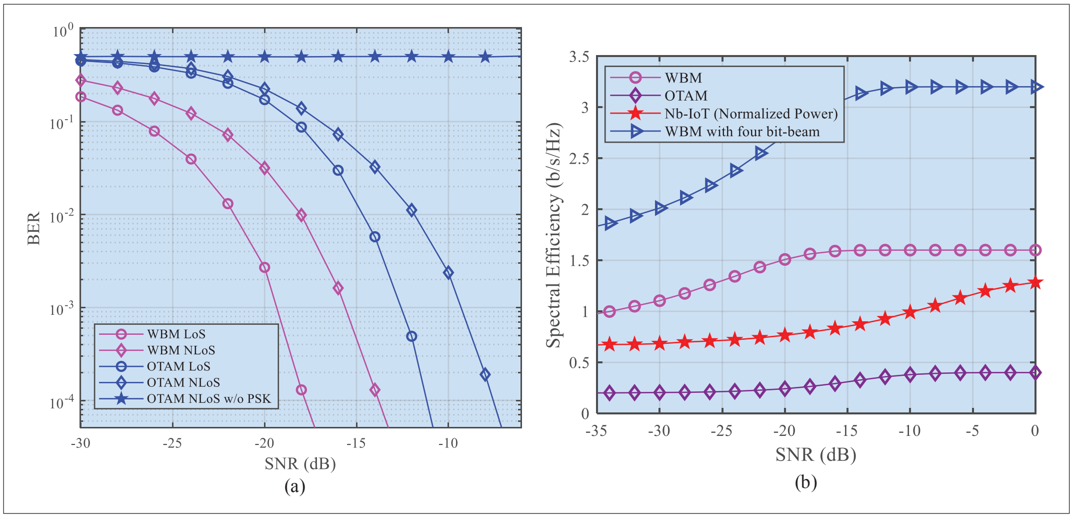


**FIGURE 5**. BER and spectrum efficiency comparison of WBM and other methods.

## BER and Spectrum Efficiency

We first simulate and compare the BER performance of WBM and OTAM with LoS and non-LoS (NLoS) scenarios. In the IoT node, the number of antennas $N_{node}$ = 16 and the number of RF chains $M_{node}$ = 1. In the AP of WBM, the number of RF chains $M_{node}$ = 8, and each RF chain is connected to $P$ = 16 antennas. As shown in Fig. 5a, for the LoS scenario, WBM outperforms OTAM by nearly 5 dB in terms of the BER performance. For the NLoS scenario, OTAM suffers a significant performance loss, which has about 6 dB performance loss compared to the multiple-bit-beam-based WBM method. It is indicated that OTAM is sensitive to channel attenuation. Hence, if the two beams experience similar channel attenuation, OTAM will suffer high transmission performance loss, which leads to a performance floor. The multiple-bit-beam-based WBM exhibits more robust performance in either scenario.

We also simulate and compare the spectrum efficiency, as shown in Fig. 5b. The transmission bit rate is related to the antenna switcher of the RF chain, set at 100 MHz. The maximal bit rate for single-link binary bit-beam WBM and OTAM is 100 Mb/s, with a bandwidth of 250 Mhz. Since the proposed WBM supports four users simultaneously accessing in SDM, the bit rate for one AP is 400 Mb/s without requiring extra spectrum resources. As expected, the proposed WBM has much higher spectrum efficiency compared to OTAM. We also compare WBM and narrowband IoT (NB-IoT) with normalized power, where the antenna gain is multiplied in the NB-IoT system for a fair comparison [14]. WBM still exhibits higher spectrum efficiency than the NB-IoT system. Moreover, if we employ the high-order-modulation-based four-bit Beam WBM, the spectrum efficiency can be further improved. The simulation results indicate that the proposed WBM can significantly improve both the transmission reliability and efficiency.

## Hardware Efficiency

The AP has been implemented with a hybrid beamforming architecture. The prototype is implemented on a platform with a 28 GHz phased array antenna with 64 antennas. The frequency range is from 26.5 to 28.5 GHz with digital beam steering ±60°, and the beam steering time is 40 μs. The beamwidth is 10° with a side lobe level of -13 dB. The number of RF chains is four with four low-resolution analog-to-digital converters (ADCs) to reduce the cost for demodulating a simple ASK signal. We use two 2 × 2 MIMO-based software defined radio (SDR) platforms as the baseband signal processing units. Although the AP is larger than for the original OTAM-based platform, the cost and power consumption can be shared by the massive IoT nodes in a practical wireless network.

Only two active mmWave components are required for the IoT node: a single-pole, double-throw switch and a VCO. Hence, the IoT node is implemented with ultra-low hardware cost and power consumption. In Table 1, we summarize and compare the proposed WBM with various wireless systems in the literature, including NB-IoT [14], WiFi [13], MiRa [11], and OTAM-based mmX [6]. According to the comparison, WBM exhibits large advantages in energy efficiency and significantly improves the spectrum efficiency over the OTAM-based mmX platform. Compared to the existing IoT-based system, NB-IoT, WBM exhibits a much higher transmission bit rate, which supports high-data-transmission-based scenarios. Although the mmWave-based platform MiRa can achieve higher bit rate and spectrum efficiency than WBM, the energy consumption and cost at the IoT node is much higher than for WBM, which is not suitable for a practical massive IoT system. The WiFi-based transmission-based

| Platform | WBM | mmX [6] | MiRa [11] | NB-IoT [12] | WiFi [13] |
|---|---|---|---|---|---|
| Frequency | 28 GHz | 24 GHz | 24 GHz | 900 MHz | 2.4 GHz |
| Peak bit rate | 800 Mb/s | 100 Mb/s | 1 Gbps | 250 kbps | 120 Mb/s |
| Bandwidth | 250 MHz | 250 MHz | 250 MHz | 180 KHz | 70 MHz |
| Spectrum efficiency | 3.2 b/s/Hz | 0.4 b/s/Hz | 4 b/s/Hz | 1.3 b/s/Hz | 1.7 b/s/Hz |
| Transmission power | 10 dBm | 10 dBm | 10 dBm | 23 dBm | 30 dBm |
| Power (IoT node) | 1.5 W | 1.1 W | 11.6 W | 65 mW | 2.1 W |
| Energy efficiency (IoT node) | 7.5 nJ/bit | 11 nJ/bit | 11.6 nJ/bit | 260 nJ/bit | 17.5 nJ/bit |

**TABLE 1**. Computation performance comparison of different search methods.

It is believed that the proposed work bridges the gap between high-speed mmWave communication and energy-efficient data transmission, which are critical for massive systems. Thus, it may have significant potential in guiding the designs of future broadband communication systems.

system (802.11n) has comparable energy efficiency with lower spectrum efficiency compared to WBM. However, as mentioned in the previous section, the sub-6 GHz spectrum is nearly congested, so it is not suitable to support future massive IoT-based scenarios.

## Conclusion and Future Research

In this article, an mmWave-based communication scheme for massive IoT connectivity, referred to as WBM, has been proposed. Different from existing mmWave communication systems, WBM transmits information by the propagation of channel attenuation with beam modulation. This improvement overcomes challenges in traditional mmWave systems, such as power hunger and high hardware cost. It is believed that the proposed work bridges the gap between high-speed mmWave communication and energy-efficient data transmission, which are critical for massive systems. Thus, it may have significant potential in guiding the designs of future broadband communication systems. This research area is still broadly open for further development and could be extended in many interesting directions, including interference cancellation, higher-order modulation, and localization by beam modulation.

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