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RETRODIRECTIVE ARRAY TECHNOLOGY

Y. C. Guo, X. W. Shi, and L. Chen

National Key Laboratory of Antenna and Microwave Technology
Xidian University
No. 2 South Taibai Road, Xi'an, Shaanxi, P. R. China

Abstract—Retrodirective arrays have garnered much attention due to the unique feature of automatically responding to an interrogator without any prior knowledge of the location of the incoming signal. This paper describes the basic concept of retrodirective array technology, discusses the three retrodirective array topologies with their advantages and disadvantages. Characterizations of the self-steering performance in a retrodirective antenna array are described. A series of array design considerations in the retrodirective array systems is presented, and further researches in this area are presented.

1. INTRODUCTION

Recent years, many RF systems have been designed with directed beam forming capability for military and civilian communication applications. These platforms of applications are located on mobile platform such as land vehicles, aircraft, and satellite. In the case of directed transmission system, phased arrays and smart antennas are used in a variety of application. The systems require use phase shifters and/or other complex beam steering and beam forming in order to perform narrow beam tracking, making them overhead-intensive systems. Retrodirective arrays [1–5] is of growing interest due to their unique functionality and relative simplicity in comparison to phased-array and smart antennas approaches.

Retrodirective arrays have the characteristic of reflecting an incident wave toward the source direction without any prior information on the source location. The analog self-phasing function in these arrays makes them good candidates for possible wireless communication scenarios where high link gain and high-speed target tracking is desired. Conventional phased-array antennas are able to steer their beams by exciting elements with phase shifters. In contrast, retrodirective arrays steer their beams automatically without any computationally intensive algorithms or hardware based phase shifters in response to an interrogating signal. More traditional beam formers using relatively complex algorithms to determine antenna patterns are slower and more expensive to implement than the retrodirective array. Compared to smart antennas that rely on digital signal processing for beam control, retrodirective arrays systems are much simpler and potentially faster because digital computations are not needed. Although the formation of the retrodirective beam is limited in that it is directed only toward the source radiator, it achieves this with no knowledge of the source location and its simplicity allows the array to track fast moving sources.

Retrodirective array have shown much potential for use in many applications [1–5], the autonomous beamsteering feature of retrodirective systems make them attractive for automatic pointing and tracking systems, microwave-tracking beacons, transponder [6], radar [7], radiofrequency identification (RFID) [8], solar power satellites, microwave power transmission [9], crosslinks for small-satellite networks [3] and complex communication systems [10–12]. A lot of work in retrodirective arrays systems have been done and exhibit retrodirective behavior in a variety of application. This paper firstly summarizes the basic concept of retrodirective array and discusses the three basic retrodirective topologies with their advantages and disadvantages, followed by a discussion of the methods for characterizing the retrodirective arrays. Then design considerations of retrodirective array architecture are introduced. Finally, further researchers of the retrodirective arrays are presented.

2. RETRODIRECTIVE TOPOLOGIES

Retrodirectivity is the behavior of the retrodirective system that reacts to an incoming signal (an interrogating or pilot signal) from an unknown direction by transmitting a response to that same direction. The response is performed without any prior knowledge of the location of the source and is completely automatic, without the use of phase-shifters or digital circuits. The retrodirective concept is based on the idea of the corner reflector for radar targets applications. With the development of high-frequency electronics, recent developed retrodirective devices have become more functional by providing modulation or active gain, making them useful for wireless communication applications.

Retrodirective behavior can be achieved with a number of different techniques. There are three methods to achieve the retrodirectivity. Basic retrodirective architecture is the corner reflector. For wireless applications, the Van Atta array [13, 14] and heterodyne phase conjugating architecture [15] are the conventional methods for realize a retrodirectivity.

2.1. Corner Reflector

The simplest type of retrodirective device is a corner reflector consisting of orthogonal metal sheets. As shown in Fig. 1, each quadrant of corner reflector forms a corner shape, it can provides retrodirectivity for any angle of incidence in the x-y plane, and is easily extended to three dimensions by intersecting the two metal sheets in order to reflect back the incoming waves from all possible angles in three dimensions space in the same direction it came from. It were originally proposed as passive reflectors for use as radar targets, as it have much larger radar cross sections than their physical size. However, the corner reflector have large size in wavelengths to minimize the effects of edge diffraction, and is difficulty in integrating electronics that are necessary for modulating the retrodirected signal, and is impossible of being in planar and low-profile features for many applications, which make corner reflectors unsuitable for wireless communications.

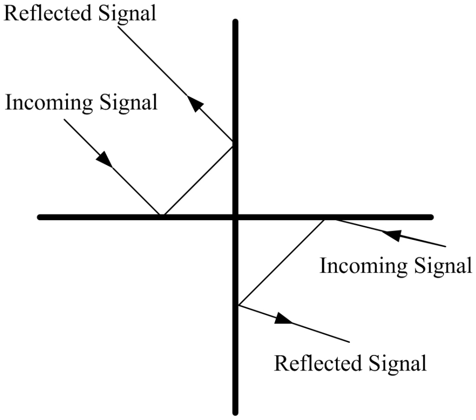


Figure 1. Corner reflector. An incident signal reflects off both faces back in the same direction of the incoming signal.

For wireless applications, it is more common to use retrodirective antenna arrays, which make themselves integrate with electronic circuits, are smaller than corner reflectors, and can be made planar and low profile. An antenna array is composed of individual radiating elements. By combining individual antennas in an array, one can achieve higher directionality and the ability to steer the beam.

2.2. Van Atta arrays

Another way of achieving retrodirectivity is through the use of the Van Atta array, which was first proposed by Van Atta [14]. It consists of pairs of antenna elements equally spaced from the array center with equal-length or multiple wavelength difference transmission lines. The arrangement of the array causes a reversal (positive to negative, negative to positive) of this phase progression for the outgoing signal, causing it to retro-reflect back in the same direction. As shown in Fig. 2, every antenna serves as both receiving and transmitting antennas. The signal received by one antenna is reradiated by its pair, causing the order of reradiation to be flipped with respect to the center of the array. Consider a plane wave incident on this array, The plane wave induces signals in each element having the phase, the signals travel through the equal-length interconnecting lines and are re-radiated. Provided the array is linear and the lines are of equal length, the re-radiated signal will have the reverse phase of the incident signal and will be retro-reflected.

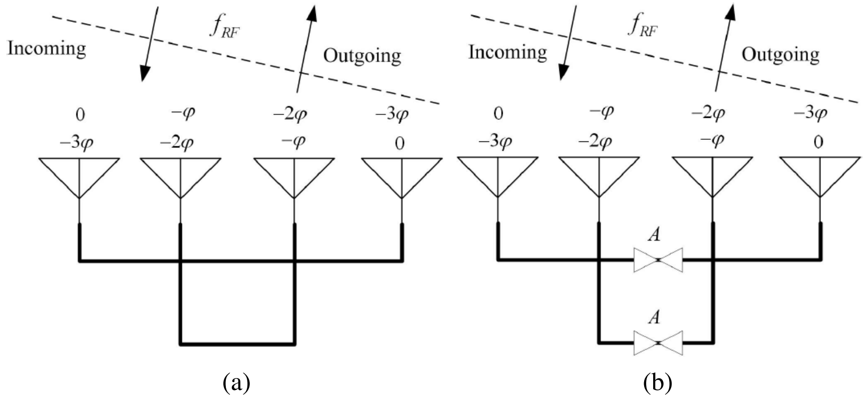


Figure 2. Schematic of Van Atta array and the relative phase for received and transmitted signals, (a) Passive Van Atta array, (b) Active Van Atta array.

The Van Atta array can be designed with a passive or active type [16, 17]. The active Van Atta array can enhance the backscattering field strength by adding amplifiers in the transmission lines [18] and accomplishes an amplitude modulation in the reradiated field [19]. As shown in Fig. 2(b), the active array may be implemented by inserting an ordinary unilateral amplifier or a bidirectional amplifier on the midway of each transmission line. The ratio of the backscattering field level of the active array over that of a passive one is exactly equal to the amplifiers' gain.

The Van Atta array is capable, in principle, of reflecting a wave incident at any angle from end-fire to broadside, but its performance is limited in practice by the directivity of the radiators. Since the lengths of the connecting transmission lines are equal, the only frequency-dependent component in the Van Atta array is the antenna element. The use of broadband antennas and nondispersive transmission lines allows the array to perform over a wide bandwidth. However, the geometrical arrangement of the Van Atta array is restricted to planar wavefronts and planar topologies, and makes it spatially inefficient for realizing retrodirectivity on many applications.

2.3. Phase Conjugation arrays

A more popular technique for realizing retrodirective arrays is based on phase conjugation using heterodyne techniques [15]. This approach uses the same idea of the reversal of a phase gradient in the Van Atta array, but phase reversal is achieved at each antenna element instead of relying on antenna pairs. In this scheme, shown in Fig. 3, each antenna is connected to a mixer, which in turn is pumped by a local oscillator (LO) with double the frequency of the incident wave. The heterodyne mixing causes the incoming radiofrequency (RF) signal at

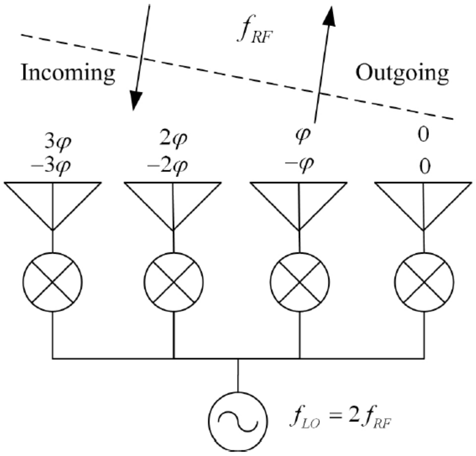


Figure 3. Phase conjugation arrays and the relative phase for received and transmitted signals.

each element to mix with a local oscillator (LO), creating the following mixing product:

$$\begin{aligned} V_{IF} &= V_{RF}\cos\left(\omega_{RF}t+\theta_n\right)V_{LO}\cos\left(\omega_{LO}t\right) \\ &= \frac{1}{2}V_{RF}V_{LO}[\cos((\omega_{LO}-\omega_{RF})t-\theta_n)+\cos\left((\omega_{LO}+\omega_{RF})t+\theta_n\right)] \end{aligned} \quad (1)$$

If the LO frequency is twice the RF frequency, we obtain the following:

$$V_{IF} \propto \cos\left(\omega_{RF}t-\varphi\right)+\cos\left(\left(3\omega_{RF}\right)t+\varphi\right) \quad (2)$$

Note that the first term in (2), which is the lower sideband product (intermediate frequency, or IF signal), has the same frequency as the incoming RF signal, but with a conjugate phase. An array of such phase-conjugating elements causes the same kind of phase reversal, resulting in a reradiated beam back toward the source direction, just as in the Van Atta array.

In this method, it is important to eliminate undesired signals so that only the desired phase-conjugated signal radiates from the array. The second term in (2) is an undesired, non-phase-conjugated signal is easily filtered and suppressed due to the large difference between this frequency ($3\omega_{RF}$) and the RF (ω_{RF}). For the same reason, any LO leakage ($2\omega_{RF}$) can also be easily filtered. Another signal that must be suppressed is the RF signal that leaks directly from the input to the output of the phase conjugator. This signal is exactly the same frequency as the desired IF signal, but is not phase-conjugated. It is impossible to filter out the RF leakage signal, as its frequency is the same as that of the phase-conjugated signal. The RF leakage creates a mirror beam of the desired retrodirective beam. Therefore, RF leakage suppression is one of the key challenges in the phase-conjugating heterodyne method. In general, balanced mixer topologies are used to eliminate undesired RF leakage signals. It should be noted that the phase conjugation is also achieved even if the RF and IF frequencies are not identical.However, the deviation between the two carrier frequencies leads to a pointing error in the return beam. The amount of the error depends on the Δf (RF-IF) as well as the incoming beam angle.

Phase conjugation arrays using heterodyne techniques can be designed with a passive or active type. Passive phase conjugation arrays using diode mixers generally provide better RF-IF isolation than do active phase conjugation arrays. The major shortcoming of passive phase conjugation arrays is the conversion loss, which limits the distance between the interrogator and the retrodirective array. However, the use of active devices such as metal semiconductor field-effect transistors (MESFETs) can provide conversion gain during the mixing process. It is possible for the active phase conjugation retrodirective array to transpond an amplified signal back to the source location, without the need for additional amplifiers by using active devices.

The phase conjugation retrodirective array has the advantage that the array elements can be arbitrarily located, not necessarily with equal interelement spacing, nor in the same plane; thus it easily conforms to the object surface. Another advantage is that, by changing the LO frequency, the reradiation wave can be easily frequency-modulated. However, the phase conjugation array needs a mixer circuit with a large-frequency difference between RF and LO signals for each array element, and an LO with double the system frequency and a corresponding distribution network from the LO to the entire array elements are required. These may make the array complicated, bulky, and costly.

Most of the recently demonstrated retrodirective arrays [1–5] are based on the heterodyne technique. This method achieves phase conjugation through hardware, only slightly increasing the circuit complexity, while eliminating the need for complex digital signal processing. This also allows for the active tracking and self steering of beam in the direction of a moving target, even without knowing its initial position, and thus is well suited for mobile communication applications.

3. CHARACTERIZATION OF RETRODIRECTIVE ARRAY

The self-steering performance of a retrodirective antenna array are characterized by bistatic and monostatic radar cross sections (RCS), the two standard measurements is illustrated in Fig. 4. Once an interrogating (incoming) signal impinges on the array under test, the retrodirected signal is transmitted back to the receiving antenna, ideally in the same direction from which it originated.

In the bistatic case, the interrogating antenna remains stationary while the receiving antenna scans over a azimuthal range, picks up this retrodirected signal. The resulting measurement in the pattern shows a mainlobe in the direction of the source, with expected nulls or sidelobes occurring as a result of the array directivity. The theoretical bistatic RCS [5] is given by

$$\sigma_{bistatic}\left(\theta,\theta_0,\varphi,\varphi_0\right)=\frac{\lambda_0^2}{4\pi}G_cD_e\left(\theta_0,\varphi_0\right)D_e\left(\theta,\varphi\right)D_a\left(\theta,\theta_0,\varphi,\varphi_0\right) \quad (3)$$

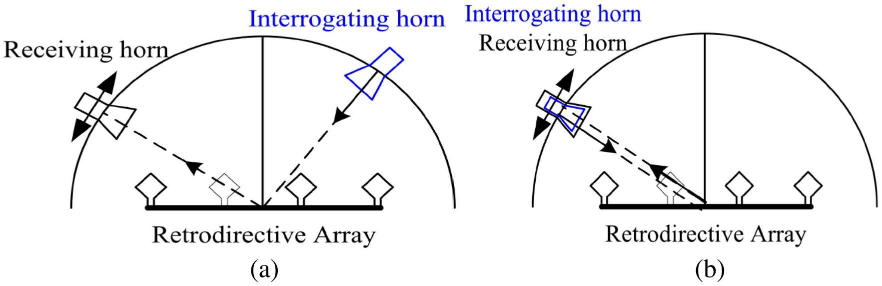


Figure 4. Retrodirective array performance is characterized by (a) bistatic RCS and (b) monostatic RCS measurements.

where θ_0, φ_0 are the RF source angles, G_c is the circuit gain, D_e is the directivity of element antenna, and D_a is the directivity of the array, given by

$$D_a(\theta,\theta_0,\varphi,\varphi_0)=\frac{4\pi\left|AF(\theta,\theta_0,\varphi,\varphi_0)\right|^2}{\int_0^{2\pi}\int_0^{\pi}\left|AF(\theta',\theta_0,\varphi',\varphi_0)\right|^2\sin\theta' d\theta' d\varphi'} \tag{4}$$

where $AF(\theta,\theta_0,\varphi,\varphi_0)$ is the array factor.

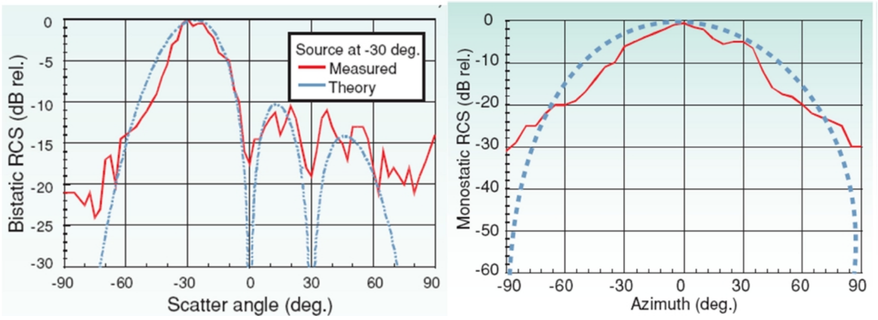
In the bistatic RCS measurement, the radiation pattern of the retrodirective antenna array is fixed since the position of the interrogating source (θ_0, φ_0) is fixed. Therefore, the directivity of the array simply depends on the angle (θ, φ), which is the position of the receiving antenna. Since the array factor is maximum at the angle of the incoming RF signal, the mainlobe of the bistatic RCS pattern should point in the direction of the source.

In the monostatic case, both the interrogating and receiving antennas are collocated and simultaneously scanned. Since the interrogating and retrodirected signals are both in the same direction, the peak of the array radiation will always be in the direction of the receiving antenna, and thus the monostatic pattern will exhibit a relatively flat pattern without nulls. The theoretical monostatic RCS [5] is is given by

$$\sigma_{monostatic}(\theta,\varphi)=\frac{\lambda_0}{4\pi}G_c D_e^2(\theta,\varphi)D_a(\theta,\varphi) \tag{5}$$

Due to the retrodirective nature of the array, the peak of the array factor will always be in the direction of the source. Therefore, the monostatic radar cross-section (RCS) pattern of a retrodirective array is simply given using the square of its element directivity multiplied by the array directivity in the source direction. Note that the directivity of the array is multiplied only once. This is because the received signal is processed at each element separately without being combined. The array factor is involved only when the phase-conjugated signal from each element is spatially combined upon transmission.

The monostatic RCS is useful in evaluating the wide angle coverage of a retrodirective array. The bistatic RCS is useful for evaluating the antiintercept capability (low sidelobe power levels) beam-pointing errors, and scan angle limitations. A typical bistatic and monostatic RCS pattern [1] is shown in Fig. 5.



(a) (b)

Figure 5. Typical RCS pattern of retrodirective antenna array, (a) bistatic RCS, (b) monostatic RCS.

4. ARRAY DESIGN CONSIDERATIONS

4.1. Antenna Element and Array Spacing

In retrodirective antenna array, the antenna element and the array spacing design must also include since they are often the limiting factor in the angular coverage of a retrodirective array. Since the radiation pattern of the array is the product of the antenna element and array factor, the maximum value of the radiation pattern of the array does not correspond to the peak of the array factor when a nonisotropic element is used. The effect of beam pulling results in a beam-pointing error (BPE), which is defined as the deviation of the mainbeam from that of the array factor pattern. Using omnidirectional antennas or an antenna element with low directivity [20–26], such as a microstrip patch, slot antennas, and printed dipoles, or increasing the number of elements reduces this error [27]. Using a low-directivity element also decreases the dependence of the retrodirected power on the interrogation angle.

Another design concern is the array spacing. The array spacing should satisfy the condition given by (6) in order to avoid scan angle limitations due to grating lobes:

$$d < \frac{\lambda_0}{(1 + |\sin\theta_{in}|)} \tag{6}$$

where d is the array spacing, λ_0 is the free-space wavelength of the interrogating RF signal, and θ_{in} is the incident angle of the incoming signal. For scanning from -90 deg to 90 deg without grating lobes, the array spacing must be less than a half-wavelength of the RF signal. The small array spacing allows the array to avoid scan angle limitations due to grating lobes, which become visible when the array spacing is too large.

4.2. Receive and Transmit Isolation

Since the interrogating and retrodirected signals share the same frequency, there is always unavoidable coupling between the interrogating and receiving antennas. Various methods, such as minimal frequency offsets, or orthogonal polarizations [28], can be used to ensure that the received and transmitted signals do not influence each other and effect the phase conjugation. A popular technique for separating the received and transmitted signals is used by slightly offsetting the frequencies so that the two signals can be resolved on a spectrum analyzer. Phase conjugation is achieved even if the interrogating and retrodirected frequencies are not identical, but the deviation between these two frequencies leads to a pointing error in the return beam [27]. The amount of the error depends on this frequency difference as well as the incoming beam angle. The shift of the main beam due to a frequency change in the array is given by:

$$\frac{\sin\theta_{in}}{\sin\theta_s} = \frac{f_{in} - f_{\Delta}}{f_{in}} \tag{7}$$

where θ_{in}, θ_s is the incoming angle and the scattering angle respectively, $f_{\Delta} = f_{out} - f_{in}$, f_{in}, f_{out} is the frequency of the incoming signal and outgoing signal respectively.

When frequency offsets is introduced into the retransmitted signal in retrodirective system, here appropriate choice of the retransmission frequency can be used to partially compensate for the effect of beam pulling by the directivity of the antenna elements. The choice lower retransmitted frequency as compared to the frequency of the received signal generates best retrodirective response [27].

4.3. Modulation and Phase Conjugation Circuits

Passive retrodirective arrays only reradiate the incoming signals without modifying the signals. This system cannot be used to transmit information and it is only a transponder. Heterodyne retrodirective arrays using an LO at twice the frequency of the incoming signal also re-transmit the original signal, additional information can be re-transmitted by modulating the LO or IF and makes this implementation useful for wireless communication. To receive and transmit information independently of the array geometry, the receiver must recover separately the incident carrier phase and the modulation used to encode the desired information. A retrodirective system based heterodyne technique using an IF can achieve this using a carrier recovery circuit. Carrier recovery circuits are therefore often used in these system and can be adapted to be used in a retrodirective implementation. It should be noted that the ability of the system to modulate the RF signal determines the complexity of the phase conjugation circuits.

Retrodirective array system consist of many channels, retrodirectivity of the array is achieved by re-transmitting the signal with the phase conjugation of the incoming signal, each channel must therefore have an identical phase shift and any difference in phase shift from channel to channel will affect the radiation pattern of the array. As the array increases in size, phase balance becomes more critical. When designing the array one must determine an acceptable phase difference between channels and design each channel taking into consideration appropriate tolerances.

5. FURTHER RESEARCH

In any wireless communication system, interfering sources can play a detrimental role to system performance. In recent years, the functionality and application of retrodirective arrays have advanced from originally simple. self-steering receiving antennas or tracking devices to more complex integrated systems, with the inclusion of modulation schemes, multiple frequency operation, reconfigurability, and even full-duplex capability [29]. However, in all cases, the main limitation is its inability to operate effectively under interference, or in scenarios with multiple interrogators, so retrodirective arrays remain vulnerable to interference. The retrodirective array capable of adaptive interference rejection will be the further research area [30, 31].

As a result of the fact, retrodirective array technology plays important roles in wireless communication systems. One of the limitations of many retrodirective arrays prototypes is the power dependence of the retrodirected signal on the interrogating signal. Since the signal must travel a distance R to the retrodirective array and back, the power level of the signal will be proportional to approximately $1/R^4$, significantly reducing the efficiency of the system. This is especially important in the case that available power is severally limited. To obtain a strong and constant retrodirected power level transmitted back to the source, the methods of decoupling the retrodirective signal from the interrogating signal must be used and do further research [3].

In a multipath environment, there are multiple paths of signal propagation that can lead to fading and interference in the communication path. In the theory, retrodirectivity completely eliminates the fading effects of multipath propagation in the roundtrip communication link. However, the mainbeam rays of retrodirective array add coherently while the sidelobe rays add incoherently, thus limiting the method in practical systems [32]. The ability of the retrodirective transceiver to reduce multipath effects and fading requires further research [33]. The response to real-world, dynamic conditions of the retrodirective array should be investigated.

Recent research on retrodirective systems has also generally focused on the performance of a single retrodirective transceiver [4]. Further research is required to establish performance of a full radio link consisting of two retrodirective transceivers, and the most economic method of integrating a retrodirective system should be investigated to reduce the cost and hardware requirements of antenna arrays [34].

6. CONCLUSIONS

Retrodirective arrays have the unique ability to retransmit signals back to its origination point without a priori knowledge. This is accomplished without complexity of digital signal processor and rely on purely analog circuitry offers system simplicity and high-speed response. This paper summarizes the methods of achieving retrodirectivity from the initial use of passive methods to the integration of active devices to increase returned signal power, introduces the self-steering performance characterized by bistatic and monostatic radar cross sections of a retrodirective antenna array. A series of array design considerations in the retrodirective array systems is presented and can play a key role to system performance. Further researches in this area are presented and will bring about new technologies and applications.

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