Experimental Performance Evaluation of Dual Antenna Diversity Receivers for RFID Readers

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Abstract **- Radio Frequency Identification (RFID) systems operating in the Ultra High Frequency (UHF) band, are exposed to fading. While state-of-the-art RFID systems employ multiple antennas, with random selection of a *single* receive path to obviate the performance losses, this paper proposes to employ antenna diversity by the combination of *all* paths applying maximal ratio combining. An experimental performance comparison of maximum ratio combining and random antenna selection with two receive antennas in a high fading environment is given, which demonstrates the superior performance of our proposal.**

I. INTRODUCTION

RFID systems have recently attracted quite some interest due to their potential of automatic inventory and tracking of items in logistic applications. Due to minimal cost and long lifetime, especially passive RFID suits the needs of many envisioned applications, and within the different operating frequencies, UHF systems provide the largest readout ranges. Due to the multipath propagation of UHF RFID systems however, the provided *reliability* of these systems hampers their ubiquitous introduction into the market. Bertocco et al. [1] recently demonstrated that with commercial RFID equipment only a fraction of tags is accessible in real world scenarios. For a readout distance of 3 m, they could access less than 70% of tags in all of the different setups they installed. Similar results have been shown in [2, 3]

State-of-the-art RFID readers (e.g. the reader of Feig Electronics [4]) employ multiple receive antennas with Random Antenna Selection (RAS, equivalently named antenna switching) in order to deal with the multipath propagation environment. Thereby, the individual receive antennas are switched alternately, and only a single receive path is considered at a time. Previously, we have introduced a realisation of Maximal Ratio Combining (MRC) for RFID readers [5], which considers all available receive paths and generates a combined signal that always provides a higher Signal to Noise Ratio (SNR) as each individual path. The implementation of the receiver on a dual receive antenna rapid prototyping platform was presented [6,7]. This paper presents an experimental comparison between the RAS and MRC techniques, which shows that the proposed receiver clearly outperforms the conventional RAS receivers.

Thorough theoretical analysis of the UHF RFID propagation channel from the reader transmitter to the tag backscatter and back to the reader receiver has been performed by Nikitin et al. for a single antenna reader receiver [8]. They also verified their models by measurements. A general model for both, a multiple antenna reader and a multiple antenna tag is proposed by Ingram et al. [9]. Furthermore, Kim et al. [10] provide a theoretical analysis of the interrogation range in Nakagami-m fading channels with multiple transmit and receive antennas at the RFID reader. Griffin et al. [11, 12] identify the theoretical performance increase employing multiple antenna readers and multiple antenna tags by calculations and simulation, especially focusing on multiple antenna tags. Additionally, Nikitin et al. [13] present experimental results on read range increase and orientation insensitivity of RFID tags with multiple RF ports. Some authors [14, 15] also propose a beam steering for a reader with multiple antennas, which can be configured to point at discrete directions. Wang et al. [16] sketch a reader receiver performing maximal ratio combining, however do not present any realisation. The performance increase of RAS readers over single antenna readers is evaluated experimentally in [17]. Additionally, work on beamforming with antenna arrays has drawn some attention recently: Authors in [18–21] propose blind beam steering by phased arrays, which allows the exploitation of an array gain in low fading environments, if the beam-pattern is facing towards the tag. Our work also analyses the receive signal constellations and accordingly combines the various diversity branches in order to achieve the best reliablitiy. The novel contribution of our paper are the implementation and experimental evaluation of maximal ratio combining at reader receivers with two antennas.

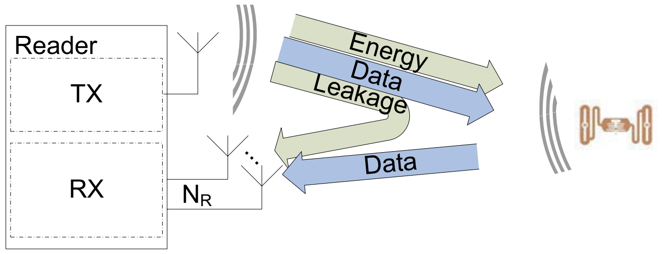


Figure 1: Communication between an RFID reader with multiple RX antennas and an RFID tag.

To our knowledge, in the presented paper the first digital RFID reader receiver performing maximal ratio combining is designed and evaluated by means of measurements. The receiver combines the signals of two antennas in an optimal way, with respect to the total signal to noise ratio (SNR) output. The advantage in contrast to random antenna selection is obvious: First, antenna multiplexing needs to multiplex all N_R receive antennas to identify the antenna with the highest SNR. Second, MRC always results in a stronger SNR than each of the single antenna receive paths. Thus, this receiver allows for a more reliable communication with tags than the conventional antenna switching receivers. The tradeoff for this increased reliability is the duplication of the reader receive frontend and the increased signal processing complexity. The receiver has been implemented for a dual receive antenna reader, however it can be easily extended to multiple receive antennas.

II. SIGNAL CONSTELLATIONS AT RFID READER RECEIVERS

Figure 1 shows the basic communication between a passive tag and a reader receiver with N_R antennas. The reader supplies the tag with energy by transmitting a continuous carrier wave to the tag, including times of uplink (tag-to-reader) communication. This continuous carrier also leaks into the j-th receive antenna ($j \in 1 \dots N_R$). While the tag absorbs energy from the provided field during downlink and idle communication cycles (tag absorb state $S^{(a)}$), it applies backscatter modulation during uplink cycles. Thereby, it mismatches its input impedance, which results in the reflection of a fraction of the received carrier wave (tag reflect state $S^{(r)}$). By switching between these absorb and reflect states according to a modulation function $a(t)$, data

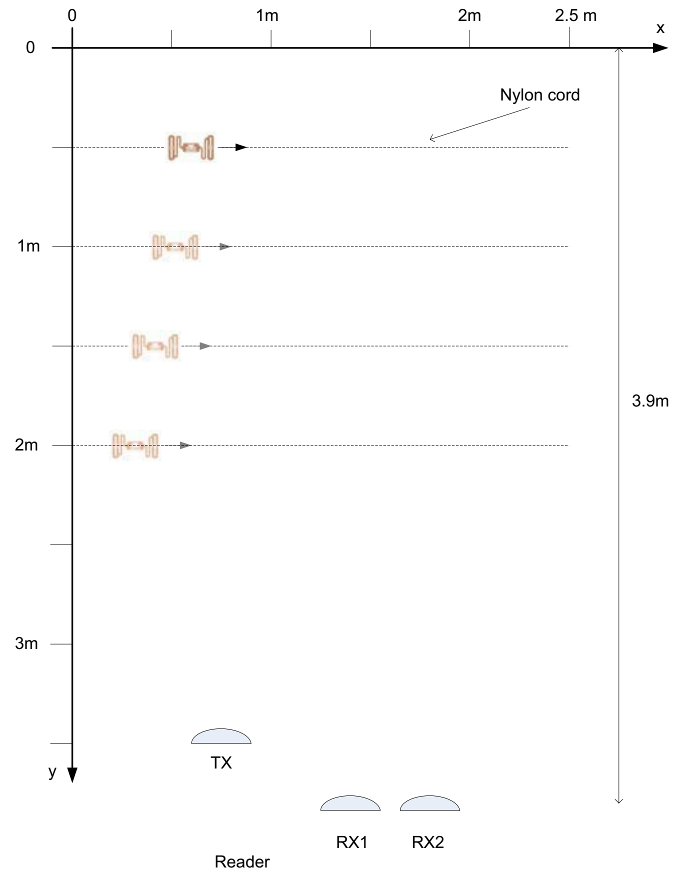


Figure 2: Measurement setup: the tag is moved on the nylon cord to positions with 0.5 m y-spacing and 0.02 m x-spacing. At each location, 2.5×10^4 measures with MRC and 2.5×10^4 measures with random antenna selection are performed. The antenna positions are: TX=(0.8m/3.5m), RX1=(1.4m/3.9m), RX2=(1.7m/3.9m).

is transmitted to the reader. According to the intuitive picture of backscatter modulation as absorbing and reflecting all the energy at the tag, $a(t)$ is assumed to realise an on-off keying modulation.

In the baseband of the j-th receive path of the reader receiver, the tag signal adds with the carrier leakage L_j and the white Gaussian noise $n_j(t)$:

$$s_j(t) = h_j a(t) + L_j + n_j(t), \quad (1)$$

where $h_j = h^f \sqrt{\Delta\sigma} h_j^b$ is the channel coefficient of the equivalent dyadic channel from the transmitter of the reader to the tag and back to the j-th receive antenna of the reader. It is composed of the forward channel coefficient h^f, the normalised differential radar cross section of the tag $\sqrt{\Delta\sigma}$ as described in [22] and the backward channel coefficient from the tag to the j-th receive antenna of the reader h_j^b. The term $\sqrt{\Delta\sigma}$ describes the backscatter modulation efficiency and models deviations from a perfect on-off keying modulation.

By stacking the receive signals $s_j(t)$, channel coefficients h_j, carrier leakage L_j and noise components $n_j(t)$ of all N_R receive antennas into the $N_R \times 1$ vectors $\mathbf{s}(t)$, $\mathbf{h}$, $\mathbf{l}$ and $\mathbf{n}(t)$, respectively, Equation (1) is equivalently reformulated to:

$$\mathbf{s}(t) = \mathbf{h}a(t) + \mathbf{l} + \mathbf{n}(t). \quad (2)$$

III. Maximal Ratio Combining

In terms of maximum SNR, the optimal combination method of multiple independent copies of the receive signal is maximal ratio combining:

$$\hat{a}(t) = \Re\left\{ \frac{1}{c} \sum_{j=1}^{N_r} (s_j(t) - L_j)\, h_j^* / \sigma_j^2 \right\}. \quad (3)$$

parameter	value
reset	10ms
lead in	3ms
lead out	2ms
encoding	FM0
Backscatter Link Frequency (BLF)	320 kHz
T_1	$31.25\mu s$

Table 1: Parameter settings for interrogation sequences according to the definitions in [23].

Here, σ_j denotes the noise power at antenna j, h_j^* is the complex conjugate of h_j and $c = \sum_j |h_j|^2/\sigma_j^2$ is a normalisation factor. As maximal ratio combining requires the knowledge of the channel coefficients h_j and the noise power σ_j^2, channel and noise power estimation is required. The estimation as well as implementation details of Equation (3) on an FPGA are provided in [5]. The carrier leakage L_j and the noise power σ_j are estimated as the mean and variance of the static receive carrier leakage during the channel idle time before the receive sequence, respectively. During this time period, which is defined as time T_1 in the standard by EPCglobal [23], neither the reader nor the tag modulate any data ($a(t) = 0$). The channel coefficient h_j at each antenna is estimated as the temporal mean $E\{\cdot\}_{t_{1pulse}}$ during the first pulse of the preamble t_{1pulse} ($a(t) = 1$): $h_j = E\{s_j(t) - L_j\}_{t_{1pulse}}$. Additionally, the receiver estimates the receive E_b/N_0 per antenna $\gamma_j = 1/2|h_j|^2/\sigma_j^2$, by determination of $E_b = 1/2|h_j|^2 t_{1pulse}$, where the factor $1/2$ results from the assumed on-off keying.

IV. Experimental Evaluation

The performance of the implemented MRC receiver is compared to the performance of a receiver with random antenna selection by means of measurements of the receive E_b/N_0 and raw Packet Error Ratio (PER).

4.1 Measurement Setup

Figure 2 depicts the spatial measurement setup. In order to actualise various fading realisations, the tag is moved to distinct spatial locations, by means of a motor driven nylon cord. At each location, the EPC code of the tag is read out by the procedure depicted in Figure 3. Additional parameter settings for the readout are provided in Table 1. The readout is repeated for 5×10^4 iterations, in which the receive antenna configuration is switched alternately between single and dual antenna mode. Thus, 2.5×10^4 readouts are performed applying MRC and 1.25×10^4 readouts are performed on each single antenna, adding up to 2.5×10^4 readouts with random antenna selection. An average of E_b, N_0 as well as the successful readouts for each antenna configuration is recorded at each position. The PER is derived as the ratio of successful readouts to the total readouts. Note, that the interrogation sequence does not apply any retransmissions by means of the "Not Acknowledged" command, if the Cyclic Redundancy Check (CRC) of the EPC code is incorrect, such that the PER reflects the performance of the successful readouts at the first trial (raw physical layer performance).

After the readouts at a certain location are completed, the procedure is repeated at the next position. The actualised positions for the measurements are separated 2 cm in the x-direction and 0.5 m in y-direction. The 2 cm steps in x-direction also allow for a spatial capturing in deep fades. The TX and RX antennas are positioned to minimise the carrier leakage in the receive paths. The antennas are commercially available patch antennas, and the TX and RX antennas exhibit a gain of 8 and 9 dBi, respectively. Furthermore, the dimensions of the measurement room allow for a maximum reader-to-tag distance of 3.4 m, as depicted in Figure 2.

The measurement is conducted in a measurement room with artificially generated fading by placing metallic reflectors into the measurement room. Figure 4 shows a photograph of the scenario with reflec-

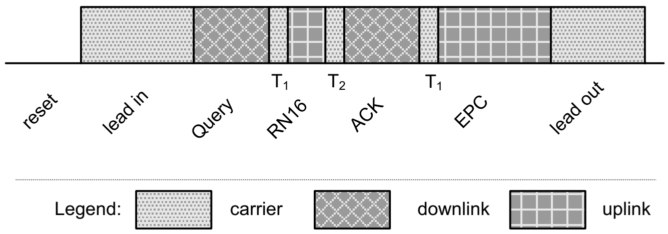


Figure 3: Interrogation sequence, applied 2.5×10^4 times with MRC and 2.5×10^4 times with RAS at each position: After a reset phase, the tag is supplied with power during the lead in phase, before the tag is activated with the "Query" command. The tag returns the "RN16" packet, which is acknowledged by the reader ("ACK"). Thereupon the tag returns its EPC code ("EPC"). After a further power supply during the lead out phase, the tag is reset by a gap in the power supply again.

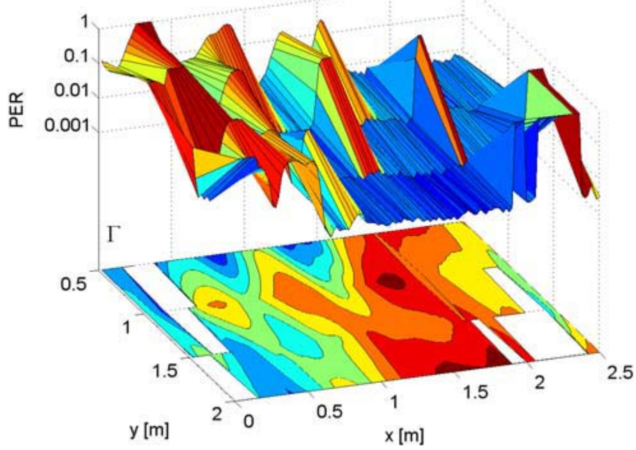
Figure 4: Measurement setup with TX (left) and RX (right) antennas. The tag is moved on the motor driven nylon cord through the measurement room. The fading in the room is generated artificially by placing one dominant ($\approx 2.5\,\mathrm{m}^2$) reflector in back left corner (position x=0 m, y=0 m) and distributing several smaller reflectors in the measurement scenario.

tors. The reflectors remain static during the measurement to circumvent a fading evolution on time at a certain location. Hence, the only movement during the measurement is the tag itself, which is mounted on the electrically invisible nylon cord to avoid an influence on the fading due to the fixture of the tag. Additionally, only the antennas of the RFID reader are placed inside the measurement room, while the frontends and digital baseband hardware reside outside. The transmit power is set to 25.5 dBm, the required measurement time to conduct the $x/\Delta x \times y/\Delta y \times \text{iterations} = 2500/20 \times 4 \times 5 \times 10^4 = 25 \times 10^6$ readouts is approximately 125 hours.

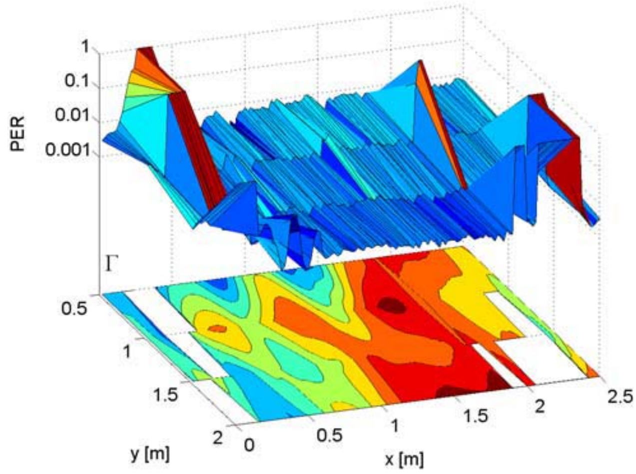
The measurement is controlled by Matlab, which activates the reader via the Local Area Network (LAN) to read out the tag at a certain position, stores the results after completion, and triggers the tag movement to the neighbouring position, before the next readout is initiated. Throughout the measurement, a single tag is used [24].

4.2 Results

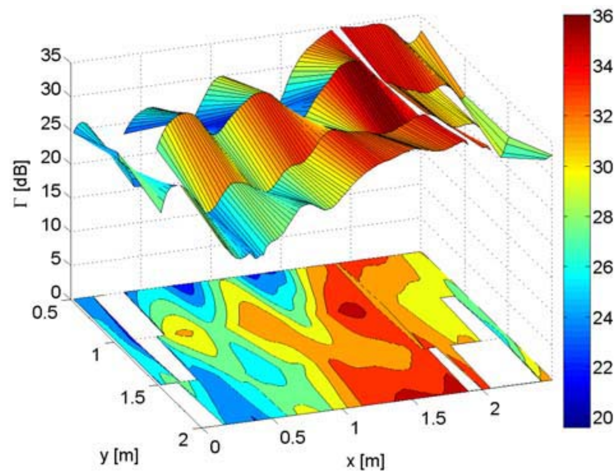
Figure 5 shows the measurement results of the random antenna selection and maximum ratio combining comparison. The x and y direction correspond to the positions as depicted in Figure 2. The surface in Figure 5c shows the measured average SNR at one antenna $\Gamma = E\{\gamma_j\}$. The contour plot below all figures also shows the average SNR distribution Γ at a single antenna at the various measurement positions.



(a) PER with random antenna selection



(b) PER with MRC



(c) Γ

Figure 5: Measurement results: (a) PER with random antenna selection, (b) PER with MRC, (c) Γ: average SNR at one antenna. The contour plot at the bottom of each graph shows the measured Γ at each location.

Figure 5a and Figure 5b depict the measured PER for random antenna selection and maximal ratio combining respectively. There are certain locations, where the tag does not respond at all, like in the back left and front right corner. These positions are also indicated by a missing Γ value in the contour plot (blank areas, as e.g. at $y = 2\,\mathrm{m}$,

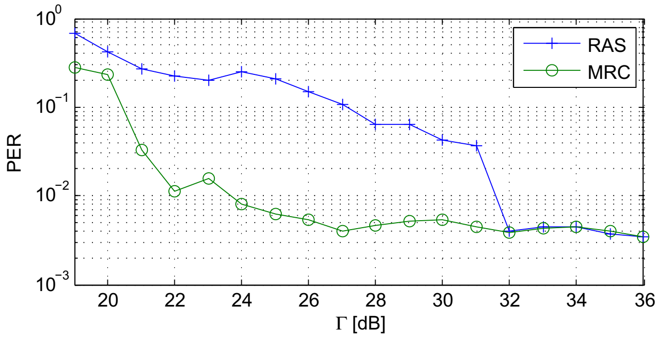


Figure 6: PER comparison of MRC and RAS.

$x < 0.2\,\mathrm{m}$). Obviously, the tag is not supplied with sufficient power, meaning that the reader-to-tag link fades or the position is out of the TX antenna illumination. At these positions, no signal from the tag is observed on the oscilloscope either. Additionally, at the isolated position x=1.76 m, y=1 m, no signal was received, although its surrounding positions show a distribution of a high Γ. This is due to shading at this single position by a metallic pole which was placed as an artificial reflector.

We observe that at positions in front of the RX antennas (x=1.4 m and x=1.7 m) Γ is higher than at positions hardly illuminated by the receive antennas (e.g. at the left side). Although tags at positions in front of the TX antenna (x=0.8 m) are expected to be perfectly supplied with energy, Γ is higher at regions where the tags are still sufficiently supplied with energy, but are better illuminated by the RX antennas. This matches with the result obtained in [25, 26], which state that a higher power supply does not necessarily lead to a better receive SNR, due to a decrease of $\sqrt{|\Delta\sigma|}$ with increasing receive power.

At those locations, where the tag was not supplied with power, obviously PER=1 for both receivers. At locations with a very strong receive signal (e.g. in front of the RX antennas), the PER of both receivers saturates at approximately 0.001. In regions with a small value of Γ (e.g. $x < 1\,\mathrm{m}$), the maximal ratio combining shows a significantly better performance than the random antenna selection. Consider for instance the case, where one return path suffers from high fading, while the other receive path experiences only small fading. Then, with random antenna selection, the high fading path will show a high number of errors, which dominate the average PER performance (PER approximately 0.5 in this case). The MRC receiver however always generates a PER smaller than each antenna, and thus even exceeds the performance of the receive path with small fading only (PER close to 0).

Moreover, Figure 6 compares the performance of the MRC receiver with the random antenna selection. The PER of positions with equal Γ of the measurement (in intervals of size 1 dB) is averaged for random antenna selection and MRC. It is observed that the PER saturates at around 5×10^{-3}. The MRC receiver shows much better performance in the range of 20 dB to 32 dB, while at even higher Γ both receivers show the maximum performance.

V. Discussion and Conclusions

In contrast to today's state-of-the-art readers, where receive antennas are simply switched and only one receive antenna at a time is considered, a realisation and experimental performance evaluation for maximal ratio combining of a dual antenna reader receiver is shown. The realisation is not restricted to two receive antennas, and an extension to multiple antennas is straightforward. The combination is optimal in the sense of achieving maximum SNR at the reader receiver. The SNR gain comes with the tradeoff of higher hardware and signal processing complexity.

An increase of the receive SNR compared to antenna multiplexing leads to an increase of the system reliability, especially in an environment with severe fading. However, this increase of SNR can also be traded into other performance goals, e.g. larger readout distance or higher data throughput.

In fact, maximal ratio combining is a diversity combining technique. Hence, in a rich scattering environment with multipath propagation and fading this receiver exploits a diversity gain. However, if the receiver encounters equal fading realisations on both antennas or even AWGN (additive white Gaussian noise) conditions, it can still exploit an array gain. It is demonstrated in [27], that the same receiver can also be applied for direction of arrival estimation in RFID, by analysing the receive signal constellation in both receive paths in a low fading environment.

The presented receiver is fully standard compliant, and hence can be applied to any UHF RFID system without any modification of RFID tags. The system performance increase comes with a modification at the reader receiver only.

The maximum ratio combining is implemented on a rapid prototyping system, which has previously been shown [5]. The measurement results show the good performance of the proposed receiver in the coverage area of the reader, and the superior performance to the common random antenna selection, which is applied in state-of-the-art RFID readers.

The proposed MRC receiver is only capable to attack fading in the backscatter link, while fading in the forward link is not addressed with this receiver. Different authors have stated, that state-of-the-art RFID systems are often forward limited, meaning that the read range is limited by the minimum required energy the tags need for processing rather than by the performance of the reader receiver [28,29]. This however only holds true for low fading environments or single antenna readers with a mono-static configuration. However, if the system is operated in an environment with severe multipath propagation and all the antennas are spatially well separated, then uncorrelated fading between the forward and the backward links, as well as between the backward links is discovered. In this case, the MRC in the backscatter channel leads to a strong system performance increase, as demonstrated by our measurements. Additionally, future RFID tags are expected to operate with even less power, such that the limitations in the backscatter channel become significant.

Moreover, the issue of forward channel fading is addressed with precoding and multiple transmit antennas [30], which is however not addressed in this paper but opens future work. Transmit diversity techniques require channel knowledge at the transmitter of the reader. The authors assume, that in setups with a strong forward and backward link correlation [10, 12, 31], the channel estimate can be used for diversity techniques at the transmitter. Such setups utilise the same antennas for transmitting and receiving, or are closely spaced. This however requires experimental evaluation of the correlation between forward and backward channel and models for multiple antenna RFID. In order to establish transmit diversity techniques, channel modeling and measuring remains a critical issue in UHF RFID, that only very limited work has been published on [29, 32–34], and which has not yet been explored experimentally for multiple antenna RFID systems.

Eventually, multiple antenna and MIMO techniques can also be employed to separate multiple tag responses in a multiple tag RFID environment, as described in [35].

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