5G Millimeter Wave Devices: The Impact on EMC Compliance Tests

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Introduction

Unless you have been spending way too much time inside an anechoic chamber over the last year, you have heard the constant buzz around 5G. In the race to be first to 5G, the marketers have been in control, and their message has become rather disconnected from engineering reality, in many cases. The fact is that a tremendous amount of engineering work on test specifications, instruments and firmware is needed before 5G user devices will fulfill the promises made by the carriers. Electromagnetic Compatibility (EMC) is definitely one of the areas impacted, but one of the technical areas least talked about. The demand is growing quickly and there is a massive market for testing these devices, so now is the time to study the issues and prepare the lab for 5G.

EMC and safety engineers can mostly avoid the hype of new technologies. Industry standards are rather slow to evolve and the test methods are generally applicable to any device with minor adaptations. For the coming wave of 5G devices, two new technologies will present a challenge to current methods and systems. The first complication is that 5G devices have the option to use two frequency ranges that are widely separated and will demand much more adaptation than an emissions limit line extension. Second, in order to take advantage of both transmission bands, 5G devices will also utilize advanced antenna systems that require several adaptations to current test methods.

In the perfect scenario, the standards would already be published before devices arrived at the EMC test lab. A 5G product family EMC standard that considers the issues and prescribes tests that ensure hundreds of millions of these devices can coexist and avoid interference with other bands would be ideal. But the reality is that the demand to claim 5G's arrival has ensured applicable standards will follow years behind deployment. Rather than product family guidance, we must pull a testing profile from several applicable standards. For example, 4G LTE device testing centered on three main categories; conformance, performance and coexistence. EMC tests were a major part of coexistence, focused on protecting spectrum from unwanted emissions that could block other communication systems. For 5G devices, test cases from 3GPP will focus on conformance; CTIA test cases will focus on performance; and the US FCC or ETSI tests will ensure coexistence with all other transmissions. This article will explore the relevant portions of 5G coexistence tests and how they will impact EMC measurement systems, chambers and procedures.

Dual Transmission Bands

Present cellular base stations and handsets transmit and receive inside a block of spectrum that begins at 450 MHz and ends at 6 GHz. This wide range comes from the vast difference in open spectrum found in each region of the world. Military, satellite, cellular, medical, industrial; everyone is competing and every country has cut up the spectrum differently. Many of the new 5G devices will continue to use the present cellular frequency range, now labeled by the 5G standards as Frequency Range 1 (FR1) and sometimes referred to as the sub-6 GHz range. Frequency Range 2 (FR2) is still taking shape, with spectrum auctions being considered for bands as low as 24 GHz and as high as 52.6 GHz. You read that correctly, the FR2 band will allow transmissions from consumer devices higher in frequency than required in most of our current EMC test standards. Many 5G devices will use both FR1 and FR2, while some will use only one band.

Applying Current Standards to 5G

The International Telecommunications Union (ITU) has proposed several applicable standards for 5G devices. These preliminary recommendations can be found in ITU-T Series K Supplement 10. Figure 1 shows a summary of the current recommendations for emissions and immunity.

Applying the current EMC standards to 5G devices is a

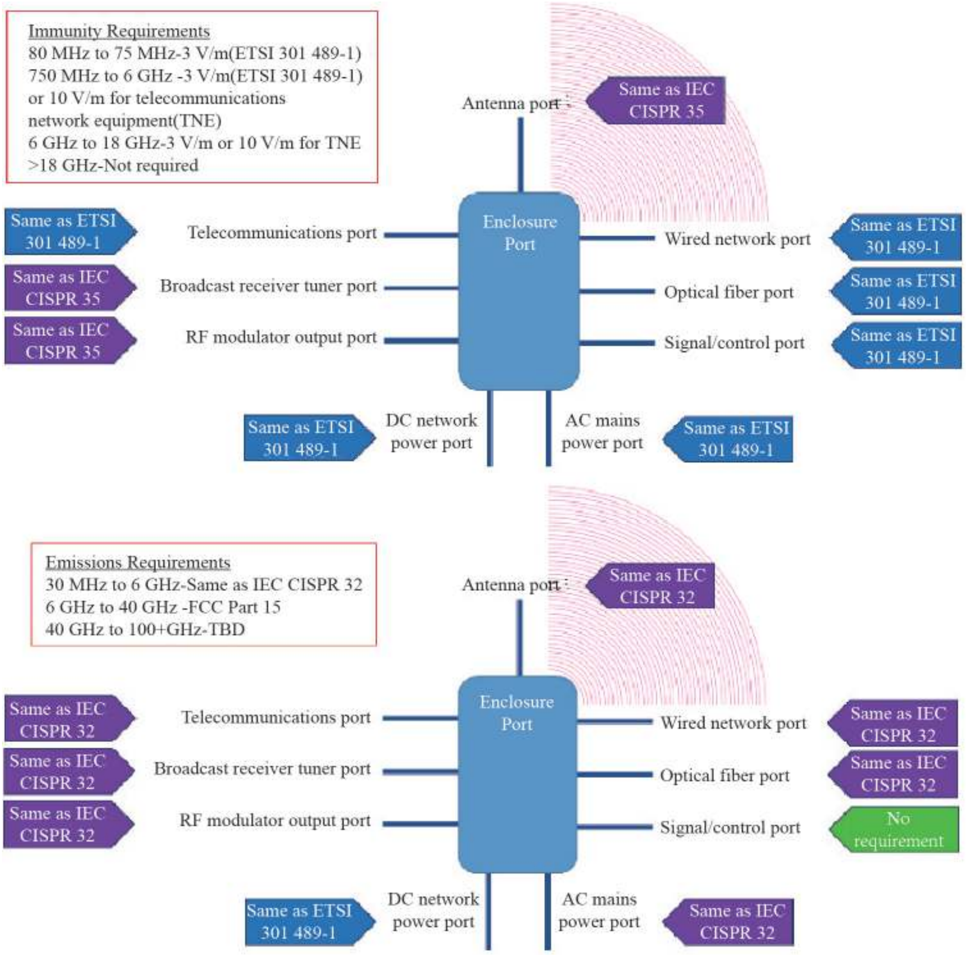


Figure 1 ITU-T Recommendations for Immunity and Emissions Tests on 5G Devices

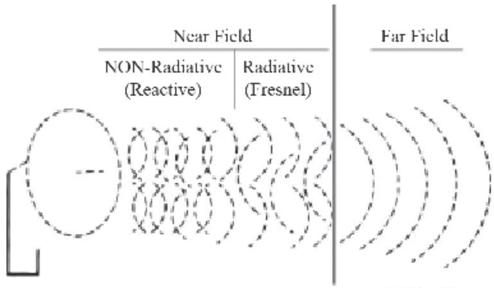
work in progress, so expect revisions to current standards that better address the new technologies going forward. For instance, CISPR radiated emissions above 6 GHz and clarifications on the applicability of audio break-through and other immunity tests are in order. US based devices that utilize the FR2 band must conform to FCC Part 30: UPPER MICROWAVE FLEXIBLE USE SERVICE. Part 30:202 and 2.1046 provide transmission power and bandwidth limits in terms of Effective Isotropic Radiated Power (EIRP). FCC Part 30 Section 30:203 defines emissions limits in terms of power spectral density for adjacent and spurious bands. Additional critical information on FCC Part 30 measurements can be found in FCC Knowledge Database (KDB) document 842590 D01. EIRP measurements are taken spherically around the device under test so that the impact of the antenna on radiated power can be assessed. ETSI utilizes EIRP measurements as well, or a closely related figure of merit called Total Radiated Power (TRP), that averages all the EIRP samples. The key difference from previous generations of cellular devices is that the antennas can no longer be assumed isotropic, radiating uniformly in all directions. Isotropic antennas may be used for FR1, but FR2 links require specialized antennas that have additional measurement requirements.

Impact on Measurement Systems

5G devices will also push the boundary on the measurement systems and environments. The antenna systems that will be used for FR2 band devices are new to consumer devices. As an extension to the MIMO concept, FR2 antennas will have many antenna elements transmitting a shifted version of the transmission. The combination of the shifted transmissions blend to make a waveform that is steered in a certain direction. These antenna systems are called antenna arrays and can be highly directional and have high gain. Using larger numbers of array elements forms narrower beams and an increased capacity to steer the beams. Unlike prior generations, no antenna ports will be available for conducted measurements on 5G devices. Size restrictions make a connector for each array element unfeasible, and the impact of the elements working together can only be measured at a considerable distance away from the antenna. Methods that measure the power at each port and then add the values, like was done for MIMO antenna systems, would yield highly complex calculations. These factors mean that measurements centering on power or emissions must be done radiated rather than conducted. Successful radiated tests will require renewed focus on antenna placement, beamwidth and path loss.

Measurement Distance

CISPR, ETSI and the US FCC want emissions amplitudes measured in the antenna far field, where possible. A quick reminder, recall that antennas have two regions defined as the near field and far field. Inside a certain distance, the electric and magnetic component amplitudes vary greatly with slight shifts in measurement position. In other words, the wave is not uniform when measured "close" to the transmitting antenna, and will yield unpredictable amplitude results in this near field region. Figure 2 shows the concept, with near field waves being unpredictable, the far field being uniform, and a solid line marking the border of the near field and far field zones.



Source: Wikipedia

Figure 2 Near Field and Far Field of Transmitting Antennas

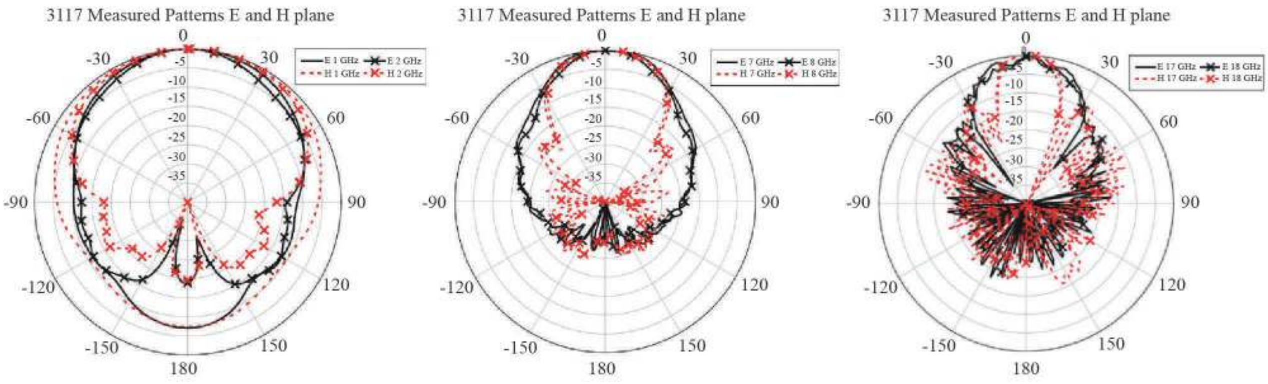
An approximate distance for measurement antenna placement sometimes used in EMC work is 3λ, or 3 times the wavelength of the frequency being transmitted. Wavelength, $\lambda = c/f$, where c is the speed of light in m/s and f is frequency in Hz. Measurement distances closer than 3λ increase the risk of placing the measurement antenna inside the near field zone of the transmit antenna. Calculating the far field distance of wireless transmitters that use the FR1 band shows potential measurement issues with the typical 3 meter test distance. Cellular transmitters begin around 450 MHz, where λ is 0.67 meters and therefore a safe far field antenna placement would be 2 meters away from the emissions source. At 6 GHz, λ is 0.05 meters, yielding a 0.15 meter far field distance. Typical Radiated Spurious Emissions (RSE) tests are carried out at a 3 meter test distance, which approaches the boundary of near field and far field for harmonics below 300 MHz. Also, notice how overwhelmingly large a 3 meter test distance is for high order harmonics of the 6 GHz band. Consider the 10th harmonic of 6 GHz, 60 GHz, has a λ of only 5 millimeters. Carefully planned movements of the measurement antenna would be needed to detect this signal.

Antenna Beamwidth

A related complexity of signal capture is antenna gain and its impact on beamwidth. One analogy for beamwidth is to compare it to various light sources. Omnidirectional antennas are similar to a bare light bulb, but antenna gain focuses the illumination of an antenna similar to the way in which a flashlight focuses light, increasing the intensity on a smaller space. Directional measurement antennas have much higher gain in the focus direction, allowing dramatically lower amplitude signals to be detected. The drawback is that high gain focused antennas are blind to signals outside the beamwidth. For emissions tests, narrow beamwidth antennas pose a risk of signal-to-antenna misalignment. Horn antennas, common to emissions measurements above 1 GHz, generally have beam widths between 30 and 70 degrees, outside of which signals will not be detected. Antenna pattern measurements, similar to those shown in Figure 3 help visualize this concept. Notice how the focus or aperture narrows with frequency and how signals outside the focus are unlikely to be detected. Measurement antennas for FR2 will have beam widths around 10 degrees being used to capture signals with wavelengths of centimeters or millimeters.

Path Loss

The path loss variation exhibited by signals of such a wide frequency range will also impact 5G emissions and power measurements. The logarithmic Free Space Path Loss (FSPL) equation, derived from Friis' transmission formula, is FSPL (dB) = $20\log_{10}\left(\frac{4\pi df}{c}\right)$ where f is the frequency of the transmission (or harmonic) in Hz, c is the speed of light in meters per second, and d is the distance between the antennas in meters. Note that this equation assumes isotropic antennas and that far field conditions are met. FSPL for a 30 MHz harmonic signal is around 11.5 dB at 3 meters. At 500 MHz, FSPL has climbed to almost 36 dB and at 5 GHz it is nearly 56 dB. Modern instrumentation, higher gain antennas, and low noise amplifiers have allowed the measurement systems to cover the range, but each adaptation has an impact. Instrument expense, fragility, and complexity dramatically increase with frequency. Higher gain measurement antennas become very directional, requiring precise positioning to capture



(a) 2 GHz *(b) 8 GHz* *(c) 18 GHz*

Figure 3 Antenna Patterns of a Double-ridged Waveguide Horn Antenna (ETS-Lindgren Model 3117)

the signals. Additionally, when low noise amplifiers are used, they dramatically limit the dynamic range of the measurements system and must be monitored for signal overload.

Many devices will use both bands, so can the same measurement system be used for FR1 and FR2 capable devices? Path loss for a 39 GHz FR2 transmitter case shows that at 3 meters FSPL is 73.8 dB. A closer measurement antenna position, say at 1 meter, cuts the FSPL to 64.3 dB. Going in very close to the device, at 10 cm, the FSPL is still 44.3 dB. As 39 GHz is the fundamental signal, harmonic multiples of this frequency will experience higher path loss. A system capable of measuring the 5th harmonic of 39 GHz will use external frequency converting mixers that must be close to, and linked with, the spectrum analyzer. Mixers also introduce substantial signal loss, complexity and cost to the system. High gain measurement antennas and low noise amplifiers are necessary for these systems, but have the previously mentioned compromises. Table 1 presents some typical values of path loss, wavelength, antenna gain and beamwidth for a system that spans the frequency range of 1-200 GHz.

Testing Beam Steering Antennas

The most important 5G technology, from an EMC standpoint, will be antenna beam steering. Current beam steering systems are being deployed on highly loaded LTE base stations, like those inside an airport, train station or sports stadium. There are several buzzwords around this technology, including beam-forming, multi-user MIMO, massive MIMO, but for our purposes, it is safe to describe this technology as a system that uses an active system of antenna elements to point a narrow transmission signal both horizontally and vertically. While beam steering will be centered on the base station side for FR1 due to size, it will be deployed on both link sides of FR2 devices (i.e. on the user equipment and base station).

Table 1 Path Loss and Antenna Values for GHz Emissions Measurements

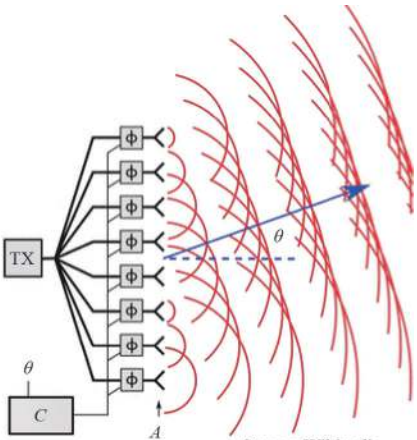
Frequency/ GHz	Free Space Path Loss @ 1 meter From Source[*]/dB	Wavelength (λ) of Emission/cm	Typical Antenna Gain[**]/dB	Half Power Beamwidth of Antenna/ degrees
1	32.44	30	2	70
6	48.00	5	10	50
18	57.55	1.67	13	20
40	64.48	0.75	18	20
60	68.00	0.5	24	11
75	69.94	0.4	24	10
100	72.44	0.3	24.7	10
200	78.46	0.15	27.5	10

[*] *assumes far field conditions and zero gain transmission antenna*

[**] *common passive double ridged and standard gain horns used as examples*

If the device under test utilizes beam steering, the 3λ approximation for far field distance should not be used. As mentioned, array antennas are not isotropic, so gain must be considered. Also, the minimum far field distance is also a function of the diameter of the antenna system, not just λ. Up to now, handheld wireless device antenna gain was minimal and the antenna diameter was small enough to ignore. Not so for antenna arrays. These must use the Fraunhofer equation to calculate the far field boundary. The equation is $R = \frac{2D^2}{\lambda}$ where R marks the beginning of the far field range (solid vertical line in Figure 1), and D is the diameter of the antenna array structure. Figure 4 shows why this is so important for beam steering systems. When the measurement is made too close to the array, the wave from each element is distinguishable from another. Only at considerable distance do the waves blend into a uniform steered wave front that can be measured accurately for amplitude.

To highlight the impact array diameter (D) can have on test



Source: Wikipedia

Figure 4 Phased Array Antenna Wavefront

distance, consider a hypothetical beam steering antenna that could be found on an FR1 base station. If the array diameter (D) were 0.5 meter transmitting at 2.5 GHz, running the calculation yields a minimum far field distance of 4.17 meters. This test could only be performed in a 10 meter chamber. Running the equation at the same frequency but with a 1.0 meter array puts the far field boundary at nearly 17 meters! The diameter of the array is a key piece of information the manufacturer must disclose. For independent test labs, this is likely an area the sales office will need to be warned about. Not many labs have a 20 meter anechoic chamber, and quoting the customer standard RSE test rates could turn into a money losing job very quickly. Array antennas could show up on many 5G associated products as the market develops, so asking the manufacturer about this will save your lab wasted test and setup time, and more importantly, might avoid inadvertently passing a device that was measured in the near field.

Beam steering antenna systems are mandatory on the FR2 band in order to have a communication link of any useable distance due to the path loss. The beam steering array must have high gain and must point narrow "pencil" beams accurately in order to maintain the link. A test system to measure EIRP and TRP at 24-50 GHz must balance all the requirements imposed by these devices. A short measurement distance is needed due to path loss, but beam steering antennas require larger volumes to be measured accurately. The antenna beamwidth and wavelength drive a need to measure spherically around the device. It is possible to build a far field measurement environment to meet these demands, but the volume of the quiet zone is very small. This means the antenna array can only measure a few centimeters in diameter. One alternative is to use a Compact Antenna Test Range (CATR) to measure FR2 devices. A CATR utilizes a reflector to focus the emissions on the measurement antenna, achieving far field conditions in a shorter path length. Compact ranges also have larger quiet zones than a direct far field chamber of the same length. Thus CATR's can accept larger array sizes and still hold the path loss within a dynamic range the instruments can measure. Figure 5 shows the quiet zone comparison between a direct far field chamber and a compact range with similar dimensions. The quiet zone size is the largest array diameter that can be tested in the chamber. CATRs are generally more expensive than far field chambers, and require additional setup time to properly focus the path for each frequency band being tested. However the quiet zone is large enough to handle any handset, tablet or laptop type device. Labs that intend to offer EMC measurements on FR2 devices should begin exploring which type of system best meets the needs of your customer base.

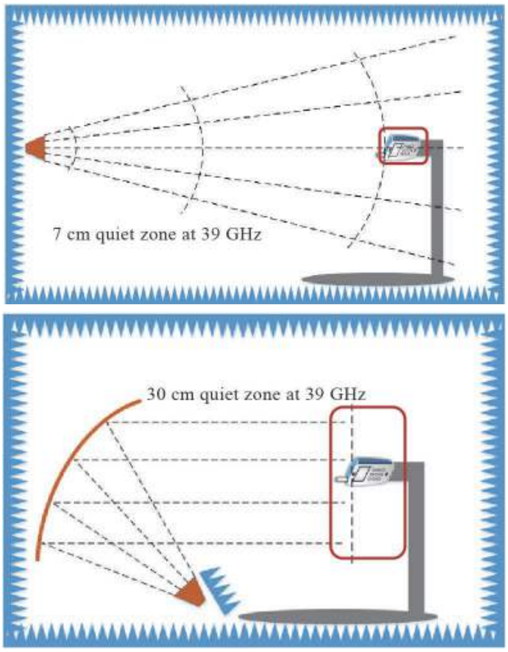
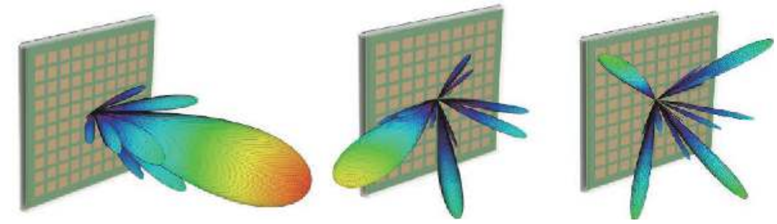


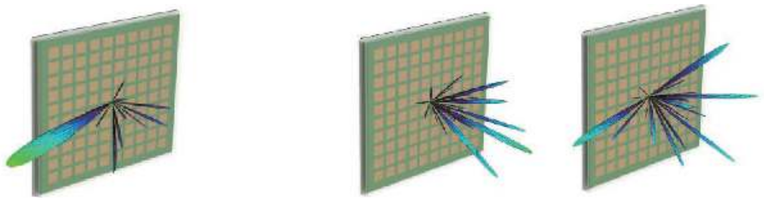
Figure 5 Quiet Zone Comparison for 39 GHz Far Field (top) and Compact Range (bottom) Chambers of Similar Size

Harmonic Emissions Testing on Beam Steering Antennas

It is important to point out one final complication antenna arrays add to emissions tests of 5G devices. Beam steering arrays also steer harmonic content in directions different than the main beam. Figure 6 is a simulation of a 28 GHz array antenna and the directions and amplitudes of transmitted harmonic energy. As can be seen, even if you have found the direction and peak of the fundamental signal, significant harmonic energy can be pointing in other directions. If the main beam now shifts to a new vector, so will all the harmonic vectors. How many beam lock positions



a) main beam, 1st harmonic *b) 2nd harmonic* *c) 3rd harmonic*



d) 4th harmonic *e) 5th harmonic* *f) 6th harmonic*

Figure 6 Radiated Spurious Emission Vectors from a Beam Steering Antenna Array
Array antennas transmit harmonics in directions far different than the main beam – a) is 28 GHz main beam transmission from a steerable antenna array, b) through f) are harmonic amplitude and direction up to the 6th harmonic

must be tested to find the worst case harmonic amplitudes?

Accurate spurious emissions tests will require knowledge about the number and location of the arrays, and the ability to control them. One device type being deployed now is an FR2 fixed wireless access unit that provides internet to the home. These devices could use a glass or wall mounted antenna array, and the harmonic content will be focused in front of and within the steering capacity of the array. For this type of device, verifying the array parameters will greatly simplify the positioning requirements and allow the technicians to focus on likely areas of signal content. A smart phone device that is capable of using both bands, and able to steer the FR2 beam around a head, hand, or obstruction will be the ultimate challenge to test. Coexistence tests will likely be done with the same system that measures conformance and performance since all must be done radiated, or Over-The-Air (OTA). Tests below 400 MHz still require a large chamber, so the clear split between EMC and OTA becomes blurred and will require a new test definition and procedures.

Summary

Emissions tests on transmitting devices have always been complex. The notch filters and antenna changes to cover the previously expected 40 GHz span required careful attention to process and procedures to get accurate results. FCC Part 30 pushes that span up to 200 GHz. Test equipment is only one aspect, test distances and positioning techniques will need to be adjusted for each device to account for the antenna present.

For some labs, a dedicated compact antenna test range will be a worthy investment. CATR's can span the full frequency range and provide more accurate results by automating the positioning and measurement functions. The directional harmonics transmitted by these antenna systems and the very narrow beam widths make measurement in large far field chambers a less repeatable approach.

5G is a massive opportunity with predictions of billions of devices being sold over the next decade. Hopefully the information presented can drive further research and help you prepare your lab for 5G success.

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