BROADBAND BUSINESS AND RESIDENTIAL RADIO ACCESS

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Abstract

This paper discusses some of the issues associated with broadband wireless access particularly directed at the non Line-of-Sight (nLoS) paths necessary for large scale deployment of Point to Multipoint networks. The paper discusses the modulation choices that can be made and how they affect the deployability of the systems. The author recommends the use of Orthogonal Frequency Division Multiplex (OFDM). Proprietary and competing systems have held back the promise of wireless access systems, as they become more complex providing greater bandwidths and services, success will only be achieved by standardisation.

I Introduction

Mr Blair has set universal internet access by 2005 as a government priority, and is considering making universal access to broadband services a pledge in the Labour manifesto.

There has been enormous interest in Broadband Fixed Wireless Access (BFWA) as a convenient method of providing access to properties where there is a competitive interest to provide service or where the user is not served by a Digital Subscriber Line (DSL) or cable. Initially operators have favoured Local Multipoint Distribution System (LMDS) frequencies where equipment has been available to provide wide bandwidth connections to large businesses accessible at short range from a Point of Presence (PoP). Technology is now becoming available which utilises lower frequencies and which provides wide data bandwidths at lower cost than the LMDS equipments. At these frequencies (2.5–6 GHz) path budgets can be created that enable longer distance operation and also nLoS operation.

Equipment manufacturers are providing a large range of equipments to choose from, some of which are based upon a circuit switched model, while others are offering the newer Internet Protocol (IP) and Asynchronous Transfer Mode (ATM) data model. Some equipments provide nLoS capability while others do not. Some equipments provide a variety of deployment options from contiguous cellular coverage through to high capacity supercells, while others are restricted to one mode of operation.

There has been much recent interest in OFDM as the modulation of choice for these lower frequencies. This has been highlighted by several industrial groups attempting to standardise on air interfaces each including a version of OFDM. There are at least seven standards bodies and many other proprietary systems being developed.

The operator has a bewildering choice to make. This paper attempts to provide some technical foundation to enable an operator to evaluate equipment suppliers offerings.

II User Requirements and wireless solutions

Including compressed voice the *average* data requirements of Small to Medium Enterprises (SME) are in the range of 32 kbps and 2 Mbps during the busy hour, while residential average data requirements are in the range 1–5 kbps with burst rate requirements of 256 kbps or greater. Clearly with the explosion of the internet and increased telephony usage rates these numbers are going to increase, at the same time improvements in compression will attempt to slow that increase. Many access systems attempt to combine the requirements of many users as close to the access point as possible in order to improve the trunking efficiency of the broadband pipes. This leads to combined data requirements in the region of 10 Mbps and an allowable contention between users. This may be used to feed up to 100 small to medium businesses or many thousands of residential users.

A key requirement in systems which combine many customers and services into one pipe, which is maintained at a high level of usage, is the implementation of Quality of Service (QoS) policies. They must use standard Internet or ATM mechanisms to advance priority packets ahead of unimportant packets. Some important packets only have a limited useful life and these must be discarded when they have exceeded their usefulness.

System solutions that provide radio access to meet this need include the Point to Multipoint (PMP) systems of LMDS and Multi Media Distribution System (MMDS) and mesh technologies. Large businesses will often be migrated to Point to Point (P-P) systems when individual capacity requirements become too large. These various systems have different deployment characteristics.

LMDS operates in the 20–40 GHz band giving Line-of-Sight (LoS) ranges up to 3 km. The radios are normally

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fairly sophisticated and costly to achieve high data rates while maximising range.

Mesh technologies try to get over the LoS problem by arranging each user to be connected to a number of other users, some of whom will be connected to a PoP. The proposed frequencies for mesh operation are 20–40 GHz and since there is a need for multiple radios at each user site these must use relatively unsophisticated modulation schemes and therefore poor performance. This performance is acceptable because the ranges to be achieved are usually below 500 metres.

MMDS solutions are attempting to provide longer ranges and get over the LoS problem by using frequencies of 1–11 GHz. The rest of this paper will concentrate on solutions for this band.

III MMDS SOLUTIONS FOR EUROPE

In this section we will look at MMDS solutions for the 3.5 GHz European Spectrum. The UK Radio Authority loaned a small piece of spectrum at 3.5 GHz to Ionica. Installation of 60,000 subscribers showed that reliable high probability of deployment could be achieved if subscriber antennas were placed high on the property and 15 m height basestations were deployed at about 5 km intervals. This fact lead to licenses being let for 3.4–3.6 GHz operation through many countries of the world.[1] Since this frequency is really too high for mobile operation it has become the frequency of choice and there are ETSI specifications for PMP operation. The EU regulatory authorities have stated that frequencies below 3 GHz should be used for mobile services while frequencies above 3 GHz should be used for fixed services.

In the US where military use is inhibiting the widescale deployment of 3.5 GHz product MMDS spectrum has become available at 2.5 GHz. There are also unlicensed bands at 2.4 and 5.7 GHz. Since the BFWA systems will normally be used for commercial service where guaranteed services delivery is important the unlicensed bands are not normally considered important. The 2.5 GHz bands have been bundled together by large operators and thus they have relatively large spectrum available even though the spectrum is often not contiguous.

In the 3.5 GHz band the spectrum tends to be contiguous and arranged in a duplex pair with the upper frequency used for the downlink and the lower frequency for the uplink. Typical licensed bandwidths that are available at 3.5 GHz range from 7–30 MHz and use a duplex spacing of either 50 or 100 MHz. The upper frequency is used for the downstream while the lower frequency is used for the upstream. In each country there is usually more than one operator licensed. Careful consideration must be given to the 'near-far' blocking effect of operators in adjacent bands using different base sites.

[1]Most of Europe, Latin America, Middle East and Asia have licensed 3.5 GHz for Narrow or BFWA

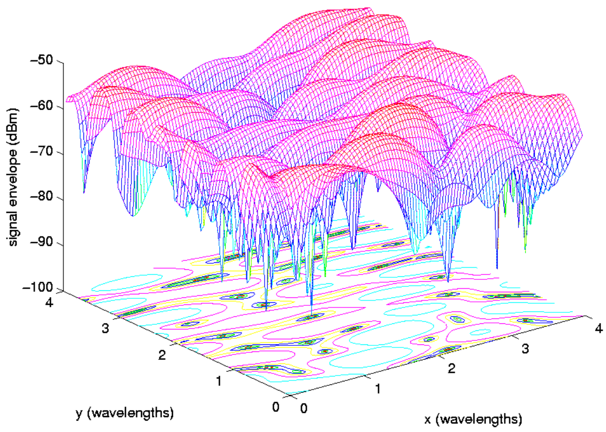

Figure 1: Spatial channel response by position in two dimensions

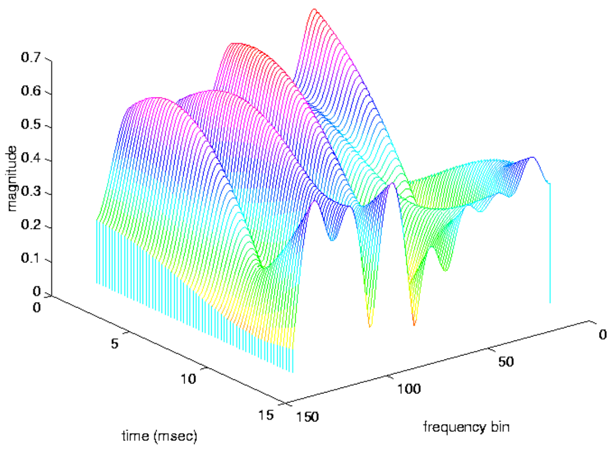

Figure 2: Spatial channel response by frequency and time

A The Channel Model

Capacity and range in BFWA PMP can be significantly enhanced by comparison with mobile systems by the use of directional antennas at the Customer Premises Equipment (CPE). These antennas are one of the features that enable modulations giving > 2 bits/sec/Hz/sector and yet allow an aggressive frequency reuse down to as low as 2. Since the propagation of signals at 3.5 GHz is significantly attenuated during diffraction, typically the CPE antenna is usually mounted at or around roof height.

Given the use of directional antennas and high CPE, the multipath is usually described by a direct ray plus a number of indirect rays which reduce in amplitude with an exponential distribution such that there are usually few components that exceed 1 µs. Erceg et al. describe their findings in [1].[2]

[2]My experience is similar to these findings except that when viewed using wider analysis bandwidths I have found the multipath to separate more into clusters.

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The strength of the direct ray is determined by the amount of obscuration of this path and in some cases will be lower than the indirect rays [2]. Trees are the major source of variation of phase and amplitude of each of these paths since they are normally taller than houses and become the main non fixed obstruction. The combination of these components leads to channel fading often described in shorthand by the Ricean model with some K-factor. In the case of highly obscured channels this K-factor can be as low as zero. The variation in the components that pass through trees can be described by a modulation which has a bandwidth of up to 2 Hz in windy conditions and much less in quiet conditions. Figure 1 gives a view of a channel with high excess path loss showing the nulls that occur in the spatial domains. Figure 2 shows the channel response by frequency changing with time.

Shared bitrates in excess of 10 Mb/s are now required in order to achieve economic deployments. The Quadrature Amplitude Modulation (QAM) symbol rate may be 3–5 Msymb/s and thus the multipath can often be greater than the symbol period for these nLoS paths.

B Deployment

Operators are still nervous of the changes taking place in the supply side of their market. They have a need to deploy in Europe in order to keep their license at the same time they know that products will shortly arrive in the market place which are standard and offer nLoS deployment.

A deployment approach being taken is to start with supercells and then migrate to a cellular configuration when the customer take up is large enough. Supercell basestations are typically mounted upon tall masts (> 100 m) and have three or more sectors to enable coverage of large areas ($> 300\,\text{km}^2$). As capacity increases the number of sectors can be increased perhaps to a maximum of 24. As the number of sectors is increased so the frequency is reused on the tower. The isolation between sectors using the same frequency needs to be of the order of 30 dB. Sophisticated antennas are now able to provide this but the basestation antenna must be high enough for the beams to be clear of any ground clutter which might cause reflections to appear in reused sectors.

Deployment of cellular coverage is very similar to mobile basestation deployment. Masts heights can be constrained by planning requirements which in the UK often require them to be less than 15 m high.

C Modulations and Codes

There are many modulations that have been used in radio access systems. The main ones are Frequency Shift Keying (FSK) Minimum Shift Keying (MSK) QAM Code Division Multiple Access (CDMA) and OFDM. These codes are often backed up with Forward Error Correction (FEC) codes. In the past simple codes have been used such as Hamming but since Viterbi presented a method for efficiently decoding convolutional codes these have been used effectively, sometimes in combination with Block codes such as Reed-Solomon. Turbo codes offer an improved performance over more conventional convolutional codes. In the future we will see Space Time Codes (STC) being provided which promise even greater capacities.

Table I: Modulation Characteristics

Modulation	Transmit efficiency	Receive sensitivity	Interference resistance	Multipath tolerance	Bandwidth efficiency
FSK	0 dB	-8 dB	-8 dB	poor	poor
MSK	0 dB	-3 dB	-3 dB	medium	medium
QAM	-10 dB	0 dB	0 dB	poor	good
CDMA	-10 dB	0 dB	+2 dB	good	medium
OFDM	-12 dB	0 dB	+4 dB	very good	good

These represent a large number of Physical (PHY) layer possibilities on which to design a system. Each one has advantages over the others, some are advantageous in line of sight and lower speed lower cost systems while others offer greater reliability when the multipath is great.

Table I shows some of the qualitative merits of some of these modulations. As you can see there are variations in the performance of each modulation to my chosen headings. Another important characteristic is sensitivity to self interference. Each modulation has a similar sensitivity to interference as it does to noise and therefore receive sensitivity and thus another column is not used.

Both CDMA and OFDM are interesting for MMDS applications. Each modulation can have a symbol length much longer than the modulation making ‘equalisation’ unnecessary. In CDMA the data is modulated onto a direct sequence orthogonalized by a Walsh code, while in OFDM the data is modulated onto a set of orthogonal carriers. CDMA can work well in a multipath environment by the optimum combining of the signals in Rake fingers but the next section will show you that OFDM in combination with powerful error correction has a rather more sympathetic method of optimising the gain in the presence of multipath.

D OFDM

This section highlights the strengths and weaknesses of OFDM for the requirements outlined in previous sections. The OFDM we are considering is one which is heavily coded using concatenated convolutional and block codes, since many of the benefits do not apply until there is considerable FEC applied across the frequency domain. This has been successfully applied to television broadcasting where there are more than half a million subscribers to On Digital which supplies 27 Mbps on each carrier occupying an 8 MHz channel using Coded OFDM (COFDM) at 64QAM $2/3$ code rate.

As can be seen in Figure 1, the channel that nLoS BFWA is trying to use is complicated by nulls. As the bandwidth

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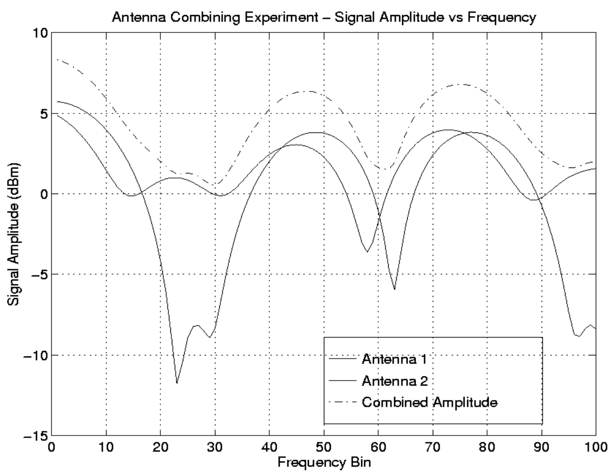

Figure 3: Optimum combining of spatially separated OFDM signals

of the signal increases so there is a greater chance of a null forming within the band of interest.

Typical QAM equalisers are unable to demodulate signals that include a deep null in the passband. This is because equalisers without Decision Feedback (DFE) are trying to form an inverse channel response function which will increase the noise level to infinity at the frequency of the null, in effect they are emphasising the signals which have least accuracy. If the equaliser incorporates a DFE then the situation is improved but the assumption for a DFE is that the error rate is low at the decision point. Since the decisions are made with a raw error rate of 5×10^{-2} then the decision process causes the equaliser to 'explode' on the information received and the errors multiply. While a null is present all symbols have the same error probability and thus a Viterbi decoder is not able to differentiate between them.

OFDM demodulators of signals which are convolutionally encoded use soft decision viterbi decoders to down weight the information in and near the nulls. This is a sympathetic approach to the channel rather than fighting the channel as an equaliser does. The consequence of this is that the bit error rate (ber) performance in nLoS channels follows an expected law of improving error rate with increasing signal the ber for QAM with equalisers often has a limit on the performance obtainable particularly if diversity is not used.

1) Diversity Even before the diversity combining of signals from two antennas, OFDM exploits the diversity of multipath by giving a modest gain when the channels are heavily dispersive.

Diversity combining of two spatially separated antennas in dispersive channels can have a greater gain than the equivalent process for other FSK and QAM modulations. Figure 3 shows the channel response of two such signals and the resultant using maximum ratio combining. As can be seen

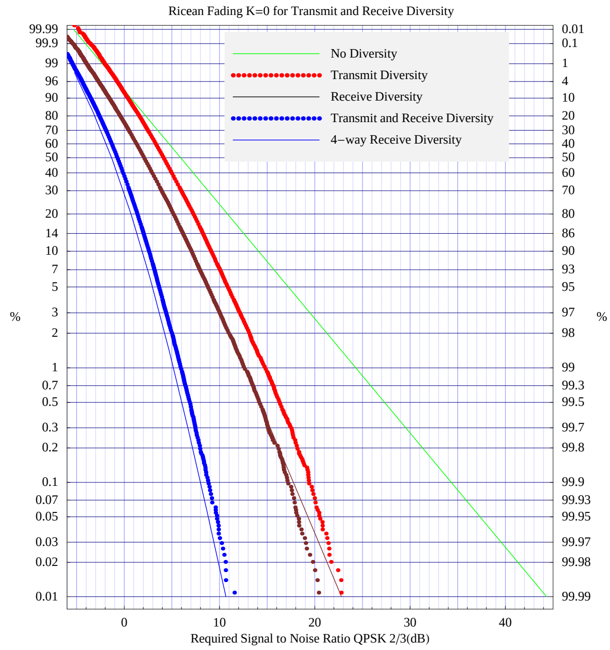

Figure 4: Mean carrier to noise requirements in Rayleigh fading channels with no dispersion for various methods of diversity

in channels with significant dispersion this is a very useful technique which is unsurpassed by most other diversity combining techniques

Figure 4 shows the mean sensitivity requirements for Rayleigh fading channels with various diversity methods. The greatest requirement shown is for no diversity. Then we see that transmit diversity improves the performance by 20 dB for 99.99% channel availability. Optimum receive diversity improves the performance a further 2 dB while transmit and receive diversity improve the performance a further 12 dB. For reference four way receive diversity combining is shown to have a further 1 dB benefit. In a PMP system these diversity methods can be used to great advantage. At the basestation site it is normal for diversity reception to be employed, the cost of extra receivers at the basestation is very small in comparison to increasing the power output of CPE equipment by even 3 dB. In addition basestation transmit diversity is a very efficient process in comparison to providing receive diversity at the CPE. Finally some customers may be in particularly difficult locations and yet they may be particularly attractive to supply service to, in this case transmit and receive diversity provides an excellent method of gaining 12 dB performance to that site.

Three criticisms are often leveled at OFDM, power amplifier backoff, complexity and phase noise. These are discussed in the following paragraphs;

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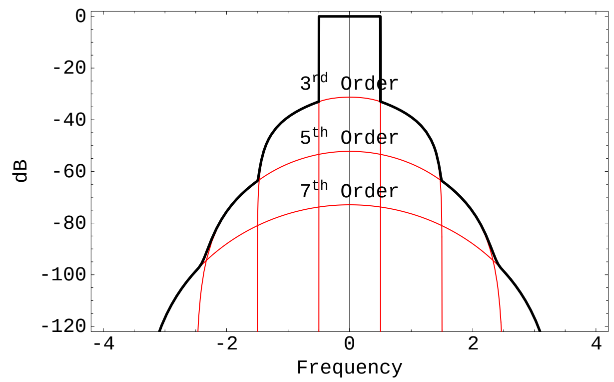

Figure 5: Distortion components in OFDM

2) Power amplifier backoff for OFDM. All broadband systems require a greater backoff than narrowband multichannel systems because of the interference requirements to other systems. Figure 5 shows the intermodulation components for OFDM, they are very similar for QAM modulations. In narrow band multichannel systems one can allow a couple of guard channels between adjacent operators without compromising system capacity much. In broadband systems the loss of one channel in say three could not be tolerated and thus the solution is to require a greater backoff giving the required adjacent channel performance. OFDM has a Rayleigh amplitude characteristic the peak to mean could be as much as 30 dB however the peaks only happen infrequently. With 64QAM modulation the peak to mean is smaller but the peaks happen very regularly. Tests and simulations show that OFDM must be backed off 1.8 dB more than 64QAM when α takes a value of 0.2 which gives a similar spectral efficiency. This loss is more than made up by the tolerance to multipath and the ability to use transmit diversity.

3) Complexity. A second problem highlighted is the complexity of demodulating OFDM. This turns out to be an incorrect assumption for the nLoS paths because the complexity of demodulating dispersive signals. Figure 6 shows the number of Complex Multiply Accumulations (CMAC) per second for a delay spread of 2 µs and an OFDM symbol length of 20 µs. As can be seen, for these settings a data rate of 20 Mbits/sec gives a substantially lower processing requirement.

4) Phase Noise. The third criticism is the extra phase noise requirement for the local oscillators. There is an improvement required of about 10 dB at frequencies of 1–1000 kHz due to demodulating the slow data rate and the multiple copies of the reciprocal mixing components of adjacent carriers. At 3.5 GHz the required performance for transmitting and receiving 256QAM are achievable for a small cost increase.

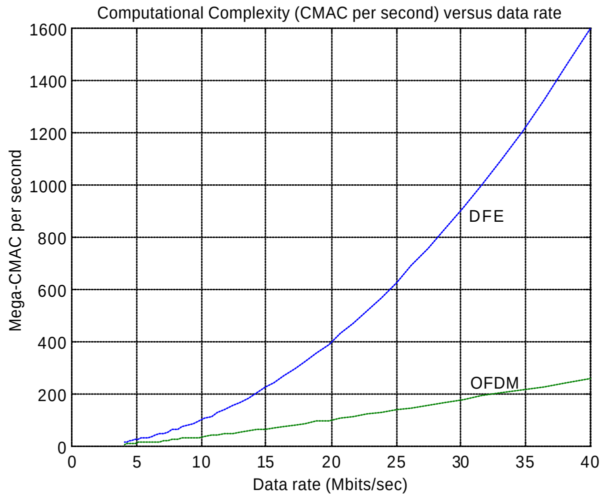

Figure 6: Computational complexity of demodulating QAM at different data rates equalised for 2 µs and 20 µs OFDM symbols

IV Standards

The Fixed Wireless Access business has been inhibited in the past by nearly all companies developing proprietary systems. These systems are becoming increasingly complicated and also the life cycle is reducing. Many businesses are realising that the future will be bigger and brighter by using standards. These will enable better systems to be developed and allow operators the choice of supplier. Systems integrators will ensure that all of the parts fit together and will often supply financing to the entrepreneurial operator.

BFWA is now benefiting from a number of standards activities. Only this year three Industry groupings and one institutional group have formed to standardise offerings. All of these industry groupings have OFDM somewhere in their charter for the PHY protocol and two of them use Data over Cable System Interface Specification (DOCSIS) for their Medium Access Control (MAC) protocol.[3] Standards groups include Broadband Wireless Internet Forum (BWIF)[4], the Wireless DSL Consortium, the OFDM Forum, Hyperaccess, Broadband Radio Access Network (BRAN), 802.16.3, 802.11a and ITU(R).

The industry is fragmented over Broadband Access in the same way as it has been for Narrowband Access. There are still a number of companies developing equipments outside any standards arena. The efforts required to achieve a stable product particularly in the MAC area often take many years longer than anticipated. The breadth of requirements that an operator will have are normally wider than one company can achieve. Examples of the breadth include CPE for busi-

[3] DOCSIS was recently evaluated in comparison to other protocols by Grover et al [3].

[4] The PipingHot Networks is a founder member of the BWIF

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ness through to residential, radio planning, installation, management, differing core networks and the need to operate in multiple frequency bands. It is the author's view that this proliferation of different methods (both standard and proprietary) will continue to inhibit the volume deployment of equipment. Manufacturers must get together and settle their differences, the result will be of benefit to all of the industry.

V Conclusions

The paper has demonstrated that OFDM is a good modulation choice for the long range terrestrial communications requirements of BFWA PMP because of the diversity gain of dispersion, two or more spatial transmitters and two or more spatial receivers.

The market for BFWA in Europe is here today with half of the countries licensed. The market will be very significant with standards progress in a similar way to Global System for Mobile Communications (GSM) standards improve each company's chances of success through creating a much bigger market.

VI Glossary

ATM Asynchronous Transfer Mode

ber bit error rate

BRAN Broadband Radio Access Network

BFWA Broadband Fixed Wireless Access

BWIF Broadband Wireless Internet Forum

CDMA Code Division Multiple Access

CMAC Complex Multiply Accumulations

COFDM Coded OFDM

CPE Customer Premises Equipment

DFE Decision Feedback Equaliser

DOCSIS Data over Cable System Interface Specification

DSL Digital Subscriber Line

FEC Forward Error Correction

FSK Frequency Shift Keying

GSM Global System for Mobile Communications

IP Internet Protocol

LMDS Local Multipoint Distribution System

LoS Line-of-Sight

MAC Medium Access Control Layer Protocol

MMDS Multi Media Distribution System

MSK Minimum Shift Keying

nLoS non Line-of-Sight

OFDM Orthogonal Frequency Division Multiplex a long symbol modulation.

PHY Physical Layer Protocol

PMP Point to Multipoint

P-P Point to Point

PoP Point of Presence of the internet

SME Small to Medium Enterprises

STC Space Time Codes

QAM Quadrature Amplitude Modulation

QoS Quality of Service

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