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A New Ray Optical Statistical Model for Multipath Characteristics Pertinent to Indoor Geolocation

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***Abstract*— A ray optics based statistical multipath channel model has been developed to describe the indoor multipath propagation including the important parameters such as path gain, time-of-arrival, angle-of-arrival and number of multipath components. Development of such a model is crucial for performance evaluation of indoor positioning systems. Based on a comprehensive ray-tracing database obtained on the 3rd floor of Atwater Kent Laboratories at Worcester Polytechnic Institute, multipath time-of-arrival relative to first arrival has been modeled using a lognormal distribution, angle-of-arrival has been modeled as a 3 peak doppler-like probability density function relative to the transmitter-receiver interconnection line. Path gains have been modeled using the information obtained from path arrival along with statistical object interactions such as reflection and transmission, and the number of multipath components has been modeled by a distance dependent exponential function.**

***Index Terms*— Indoor wireless channel, positioning, geolocation, statistical multipath behavior, ray optics**

I. INTRODUCTION

WIRELESS propagation mechanisms have been extensively studied for outdoor medium following the advances in satellite and terrestrial communication systems. With the advent of cellular systems, propagation modeling has gained importance in order to deploy a certain system as efficiently as possible in a given environment. Many researchers worked on both urban and suburban propagation models in an effort to accurately model the signal characteristics such as received power and multiple arrivals due to scattering and reflections.

Earlier studies for outdoor or equivalently macrocellular environments involved derivation of statistical and geometric models for time-of-arrival (TOA) and received signal strength (RSS) for performance evaluation of long range wireless communication systems [1]–[3]. Dominant propagation mechanisms for these environments are the deterministic path loss, slow (shadow) fading caused by large obstacles and fast-fading caused by local scatterers and the motion of the receiver. For path loss, models ranging from the basic Friis transmission equation, to more sophisticated urban models such as the COST231-Hata model [4] have been applied with certain degrees of accuracy to real life applications. Slow fading is usually assumed to be lognormally distributed and fast or equivalently multipath fading, has been modeled by using a rayleigh distribution [5].

Indoor propagation environment, on the other hand, introduces unique challenges due to existence of rich and densely spaced multipath components (MPCs). Some of the earlier works for indoor modeling can be given as [6]–[10]. Different approaches need to be considered in order to effectively model the propagation mechanism for such environments [11]. Since distances are ranging from tens of meters to couple of kilometers for outdoor, multipath arrivals caused by reflections can easily be resolved by using relatively lower bandwidth signals. However, in order to resolve the dense MPCs caused by numerous reflections in a cluttered environment, larger bandwidth signals, such as ultra-wideband (UWB), need to be considered. FCC's UWB definition of at least 500MHz [12] would be able to resolve MPCs that are as close as 2ns corresponding to roughly 60cm separation between path arrivals. Owing to very large bandwidth of these signals, UWB is more robust against multipath fading which is more dominant for narrowband systems. With its ability to resolve finely spaced MPCs, wideband and UWB systems have also been actively researched in the context of channel modeling and ranging [13]–[15] for indoor positioning systems.

Hence for accurate modeling of indoor propagation for positioning applications, we would need to have as much information as possible regarding the features of MPCs. Consequently, a substantial work is devoted to this field and researchers obtained statistical and empirical models for the indoor environment. Although a majority of these studies focused on high data rate, short range communication applications [16], [17], studies do exist that place more importance for indoor geolocation specific features such as modeling the absence of direct path and errors associated with it [11], [18], [19]. Communications applications focus mostly on the delay spread and received signal strength which are indicators for the data rate limitations and overall coverage [4], whereas individual TOAs of MPCs relative to the line-of-sight (LOS) arrival together with their angle-of-arrivals (AOAs), path gains (amplitudes) and the total number of MPCs need to be known to employ channel aware precise positioning systems that can exploit multipath diversity.

In this paper, based on an extensive database of measurement calibrated ray-tracing (RT) results on the 3rd floor of Atwater Kent Labortaories (AK) at Worcester Polytechnic Institute (WPI), a typical indoor environment, we propose ray optics based statistical models for the features of the MPCs. In section II, we introduce the basic indoor channel

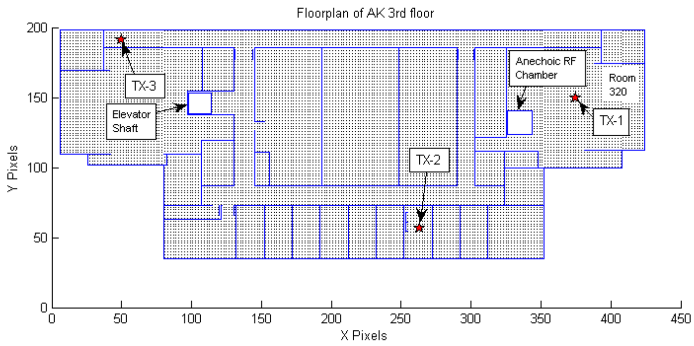

Fig. 1. Map of AK 3rd floor showing transmitter/receiver locations and floorplan features

and propagation mechanisms. Section III introduces the RT simulation environment, data extraction and analysis. Section IV presents the overall proposed channel model. Section V gives the comparisons of the proposed models with the results obtained. Finally, section VI concludes the paper with some possible future directions.

II. Indoor Channel Propagation Model

Exact modeling of indoor channel requires tedious solution of Maxwell's wave equations for complex structures. Even though computational electrodynamics methods such as finite-difference time-domain (FDTD) are available, they are not time-efficient and requires high utilization of computational resources. As an alternative there exist RT solutions which is based on ray shooting principles. In terms of speed and conformance to real-world measurement data RT techniques are preferred for most indoor propagation prediction studies [20]. Given a transmitter location, rays are shot in every possible direction (with a certain discretization) and they interact with the objects through either reflection and transmission on which we will elaborate below. The rays, that can reach the receiver through geometric propagation, are considered to be the components of the CIR if they are within the detection threshold.

Indoor multipath propagation is dictated by various interactions of the MPCs by the various types of objects such as furniture, walls, doors and windows which have varying degrees of effect on signal propagation. The two main interactions are namely the reflection and transmission. Diffraction and diffuse scattering can be ignored for indoor environments [21]. Based on the material properties, these objects will have different reflection and transmission coefficients. Metal and steel surfaces, for instance, can be considered as specular reflectors but no or very little transmission will take place. On the other hand, materials such as wood or brick, will both reflect and transmit the incoming ray after a certain loss. Each reflection and transmission has a corresponding loss coefficient and will decrease the path power accordingly.

In RT techniques, each ray is considered to be an infinite bandwidth optical ray. This representation of MPCs is also in line with the channel model that was first proposed by Turin [22] and is well suited to describe RF propagation in multipath-rich indoor environments.

The general multipath channel can be given as

$$h(t,\Theta) = \sum_{i=1}^{Lp} \beta_i e^{j\phi_i} \delta(t-\tau_i)\delta(\Theta-\theta_i) \tag{1}$$

where L_p is the number of MPCs, and β_i, τ_i, θ_i and ϕ_i represent the path gain, TOA, AOA and phase, given by $\phi_i = -2\pi\tau_i/\lambda$, of the i^{th} path, respectively.

Based on (1), we can easily see that the unique features of a single MPC can be characterized by its TOA, AOA, and path gain. Number of MPCs is also an important feature and can be an indicator of how densely cluttered a certain environment is. In the following section we describe the RT environment for data extraction and later we obtain the models and related parameters for each of these features as obtained from the RT simulations.

III. RT Environment and Data Extraction

In order to obtain the parameters of the proposed model, we utilized a calibrated RT tool [23], and developed realistic indoor floorplans of the AK Laboratories at WPI. We have produced an extensive database of CIRs for the 3 different transmitter locations (denoted as TX-n, n=1,2,3) and about 13500 receiver locations for each transmitter location for a total of more than 40000 CIRs. Each CIR is composed of all relevant path parameters such as TOA, AOA, and path gain. Floorplan consists of the rectilinear layout of the 3rd floor of AK with metallic doors and dielectric walls. Elevator shaft and the anechoic RF chamber in room 320 have been modeled like metallic doors as almost perfect conductors, and hence giving us a more realistic propagation environment. The floorplan with the transmitter and receiver locations is depicted in figure 1.

IV. The Proposed Channel Model

This section presents the overall indoor channel modeling scheme. We first present the statistical models for the TOAs and AOAs of the MPCs. Then, based on the TOA, we obtain the path gain subject to a certain number of reflections and transmissions which we obtain through the statistics of object interactions. Finally, we obtain the expected number of MPCs based on a distance dependent exponential formula.

Various channel models are present in the literature that either use geometrically based statistical channel models (GBSCMs) [24] or use statistical fitting methods based on empirical or simulation data [6], [25]. GBSCMs present an optimistic approach which is usually not encountered in real-life scenarios, such as single bounce or a circular/elliptic scatterer region assumption. On the other hand, statistical fitting methods may not be applicable to a multitude of environments, since data from measurements or simulations would be limited. However, since real propagation environments are considered, these models might represent the actual indoor RF channel better.

The parameters for these models have been obtained through statistical best fit approaches that best represent the RT simulation results. We will give an outline for each model in this section and numerical analysis and related parameter values will be given in the next section along with their discussions.

A. Model for the TOA, τ_i

Based on our extensive RT simulations we propose the use of lognormal model for the distribution of relative TOAs as

$$f_\tau(\tau) = \frac{1}{\tau\sigma\sqrt{2\pi}} e^{-\frac{(ln(\tau)-\mu)^2}{2\sigma^2}} \tag{2}$$

We should note that this model is actually the distribution of MPC TOAs relative to the LOS distance, hence this way we are also incorporating the effect of transmitter-receiver separation distance into our model. A similar approach has been followed by [26] as they modified the model in [6] by incorporating the LOS distance. Another TOA modeling approach is the modeling of path inter-arrivals as presented in [25].

Thus the absolute TOAs can be given as:

$$\tau_{abs}(r) = r/c + \tau \tag{3}$$

where r is the LOS distance and c is the speed of light.

The use of lognormal modeling for the TOA has also been proposed by [27] and our findings also confirm the suitability of this model for TOAs of MPCs. Other well known distributions such as Beta and Weibull have also been considered, however, conformance in the maximum-likelihood-estimation (MLE) sense is found to be best for lognormal distribution.

B. Model for the AOA, θ_i

AOA modeling of indoor channel can be considered as a relatively recent study area compared to TOA, since early systems were mainly omnidirectional systems that did not exploit the direction of MPC arrival. With advances in antenna technology and signal processing techniques, AOA has gained importance especially for MIMO systems and systems employing spatial diversity through beam steering. Another important use of AOA is in the field of geolocation, where AOA information can be used to increase accuracy coupled with other information such as received signal strength (RSS) and TOA. Some previous works in AOA modeling include the GBSCM approaches and measurement fitted statistical models [26].

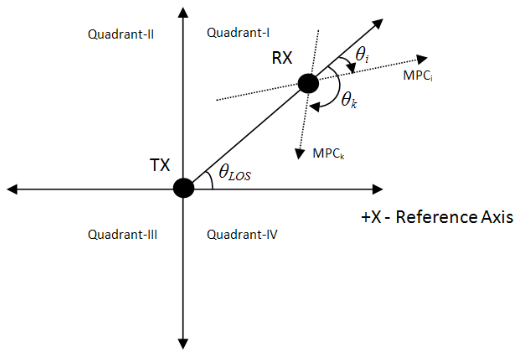

Fig. 2. Illustration of MPC Arrivals

The results we have obtained through the simulations suggest a strong dependence of the MPC AOAs on the interconnection line between the transmitter and the receiver. In other words, the MPCs tend to arrive close to the LOS path. In order to describe this behavior, we define the MPC AOA relative to the AOA of the LOS path which is a deterministic value given the locations of the transmitter and the receiver. This is depicted in figure 2.

As a result of the simulations, we can see strong angle components at $-\pi$, 0, and π. This suggests us a 3-peak doppler-like angle spectrum. Our model is, in fact, the superimposition of two doppler-like spectrums centered around $-\pi/2$ and $\pi/2$ respectively and with a span of π radians which show an accurate representation of AOA distribution around the LOS component.

The model for the relative AOA can thus be given as

$$f_\theta(\theta) = \begin{cases} \frac{1}{\pi^2\sqrt{1-\left(\frac{\theta+\pi/2}{\pi/2}\right)^2}} & -\pi < \theta < 0 \\ \frac{1}{\pi^2\sqrt{1-\left(\frac{\theta-\pi/2}{\pi/2}\right)^2}} & 0 \le \theta < \pi \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

With the piecewise integration of (4) we get the CDF as

$$F_\theta(\theta) = \begin{cases} \frac{1}{2\pi} sin^{-1}(\frac{2}{\pi}\theta + 1) + 1/4 & -\pi < \theta < 0 \\ \frac{1}{2\pi} sin^{-1}(\frac{2}{\pi}\theta - 1) + 3/4 & 0 \le \theta < \pi \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

Hence the absolute AOA of a certain path with respect to a certain reference is given by

$$\theta_{abs}(\theta_{LOS}) = \theta_{LOS} + \theta \tag{6}$$

In (6), θ_{LOS} is computed as

$$\theta_{LOS} = atan2\,(TX_y - RX_y, TX_x - RX_x) \tag{7}$$

where $atan2$ is the 4-quadrant inverse tangent and TX_x, TX_y, RX_x, RX_y denote the x, y coordinates of the transmitter and receiver respectively. 4-quadrant inverse tangent takes on values from $[-\pi, \pi]$ and is particularly useful for identifying angles with respect to a certain reference axis such as X-axis. A formal definition of $atan2$ is presented in the appendix.

C. Model for the Path Gain, β_i

Modeling of the path gains and total RSS have been an area of extensive research for the design and performance of wireless systems, since accurate modeling of RSS is important both for communication and geolocation systems alike. Primary focus has been on outdoor environment for relatively narrow band systems, since earlier systems were developed for long range low rate communications. Due to the nature of narrowband signal, path gains were conveniently modeled as Rayleigh distribution which is attributed to the multipath fading. Signal components are vectorially added according to their phases and resulting vector could exhibit drastic changes even for short periods of time. The total power for these signals can be given as

$$P_r = P_0 \left| \sum_{i=1}^{L_p} \frac{a_i}{d_i} e^{j\phi_i} \right|^2 \tag{8}$$

where P_0 is the power of the signal at 1m, L_p is the number of MPCs, a_i is the overall reflection/transmission factor for ith path after j interactions expressed as

$$a_i = \prod_j \alpha_{ij} \tag{9}$$

with α_{ij} being either the reflection or the transmission coefficient for the jth interaction ($\alpha_{ij} = R$ for a reflection, and $\alpha_{ij} = T$ for a transmission), and $d_i (= \tau_{abs} \times c)$ is the total distance the MPC has traveled.

However, for wideband systems, since individual paths can be isolated to a certain degree, their phases do not contribute to amplitude characteristics of the channel. In this case, total power is found by squaring the path gain of each arriving path and summing them over all the arrivals. This can mathematically expressed as

$$P_r = P_0 \sum_{i=1}^{L_p} \left| \frac{a_i}{d_i} \right|^2 = \sum_{i=1}^{L_p} |\beta_i|^2 \tag{10}$$

Most studies model P_r distribution based on statistical methods similar to τ and θ. Here we are going to follow the work by [10] to obtain path gains by statistical interactions of each path with the walls either by transmission or reflection. The path gain, after a total of $m + n$ interactions (a total of m reflections and n transmissions) can be given as

$$\beta_i = \frac{A}{\tau_{abs} \times c} \prod_j \alpha_{ij} \tag{11}$$

where A is the signal amplitude at 1m given by $A = \sqrt{G_t G_r} \frac{c}{4\pi f} = \sqrt{P_0}$, τ_i is the TOA of the ith path. Here G_t, G_r, and f are the transmit and receive antenna gains and center frequency of the signal respectively. For isotropic antennas, $G_t = G_r = 1$ and for our modeling approach we have chosen $f = 1GHz$.

For the distribution of object interactions we have observed a very good conformance to Poisson distribution which has also been observed by [10]. Furthermore, both reflections and transmissions can be modeled separately as independent Poisson distributions. We will model the distributions of number of reflections, m, and number of transmission, n, as follows

$$P(M = m) = \frac{\lambda_r^m}{m!} e^{-\lambda_r} \tag{12a}$$

$$P(N = n) = \frac{\lambda_t^n}{n!} e^{-\lambda_t} \tag{12b}$$

where λ_r and λ_t are the average number of reflections and transmissions respectively.

Although number of reflections and transmissions are dependent on the distance an MPC travels, this method provides a simpler and straightforward modeling. For a more detailed analysis of path gain modeling one can refer to [10].

Hence, given the transmitter-receiver distance τ_{abs} as obtained from the TOA model, m and n as obtained from (12a) and (12b), we can use (11) to estimate path gains.

D. Model for the Number of MPCs, L_p

Number of MPCs is also an important parameter in estimating the characteristics of the indoor channel. It is related to the degree of the clutter around the transmitter and/or receiver. Unlike the outdoor propagation medium, a large number of MPCs will be present in the indoor environment. Based on our observations we are proposing the distance dependent exponential model for the number of MPCs. The number of MPCs tend to decrease as the separation of the transmitter and receiver increases. This is actually an expected result, since the power of MPCs is inversely proportional to the distance they travel. The more the distance, the lower the chance for the detection of a certain MPC. However, exact number of paths is also very dependent on the nature of the propagation such as the existence of metallic obstacles or long corridors which act as waveguides. In those situations L_p might not be dependent directly on the distance. This is also shown in figure 9 where we see high number of paths occurring from the transmitter (TX-3) for the points along the corridor.

We should also note here that since RT simulations are based on infinite bandwidth assumption, it gives us all possible rays reaching the receiver. When bandwidth restrictions are imposed, paths that are closer to each other than the MPC resolution interval will be detected as one path. Hence we expect a decrease in the number of paths as we start to decrease signal bandwidth.

Our proposed model for the L_p is given as

$$L_p = a_1 e^{-r/a_2} \tag{13}$$

Although more sophisticated models can be used for a more accurate representation of L_p, this model is found to be a good compromise to describe the distance dependence of number of MPCs. The parameters of the model, a_1 and a_2 have been obtained through non-linear least squares optimization.

V. Simulation Results

In this section, we present the comparison of the proposed model and RT data with respect to TOA, AOA, Gain and number of MPCs.

Figures 3 and 4 show the CDF and histogram of the TOAs relative to the first arriving path. We can see a close match with the RT data. Beta and Weibull distributions can also describe relative TOA to a certain degree accuracy, however lognormal distribution has been found to be the best performing model. The model parameters are: $\mu = -16.02$ and $\sigma = 1.06$. Since in one of the scenarios, transmitter (TX-3) is located at one end of a 50m long corridor on the 3rd floor of AK, results also show the presence of higher order reflections occurring at the ends of the corridor. This can be seen in the histogram of the relative TOAs in figure 4.

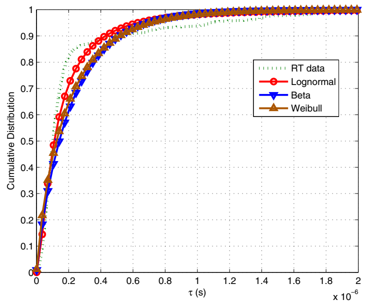

Fig. 3. Cumulative Distribution for the relative TOA, τ

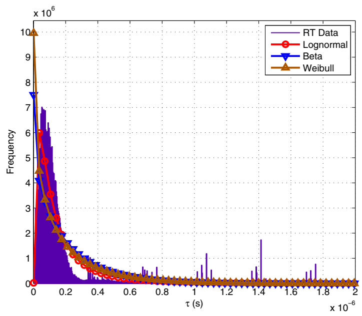

Fig. 4. Histogram for the relative TOA, τ

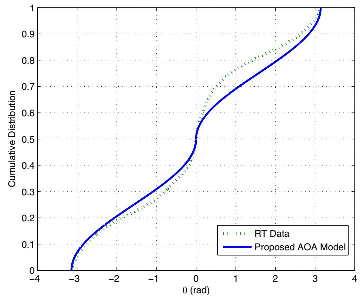

Fig. 5. Cumulative Distribution for the relative AOA, θ

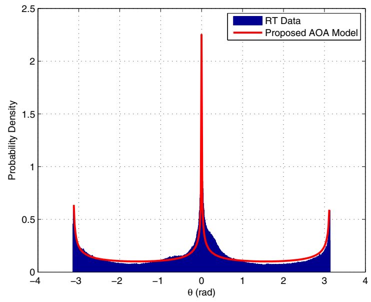

Fig. 6. Probability Density for the relative AOA, θ

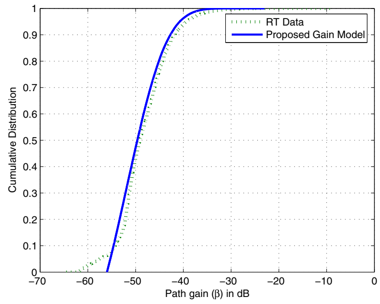

Fig. 7. CDF for Path gains using the proposed model vs RT Data

Figures 5 and 6 show the CDF and PDF of the AOAs relative to LOS component. We can see the strong dependence of the multipath arrivals on the LOS path since most paths tend to arrive around $-\pi$, 0, and π radians around the LOS.

Figure 7 shows the CDF of path gain, β, obtained using the proposed model vs the path gain from RT data. We see a very close match between the model and the observed data. The threshold for path power has been fixed at -56 dB for the RT. The small fraction of paths that are below -56 dB can be attributed to the design of the RT software which checks for threshold at each object interaction rather than a continuous check during propagation. Hence a path might have incurred additional path loss since the last object interaction at which point it might have had higher power than the threshold.

Figure 8 shows the CDFs for the number of reflections and transmissions for the proposed Poisson models vs the RT data. From this figure we see the suitability of the Poisson Model for the number of object interactions. For the coefficients of reflection and transmission we have used an average reflection coefficient of $R = 0.7$ and a transmission coefficient of $T = 0.5$. These values have been taken from [10].

Figure 9 shows the dependence of number of paths, L_p, to distance. We can see the decreasing trend of number of MPCs with the increasing separation between the transmitter and receiver. This is an expected result since more and more paths will be below the detection threshold with increasing distance. The exponential model parameters for the number of MPCs has been obtained through LS optimization. The existence of high order reflections for the corridor points leads to almost same number of MPCs which can also be seen in figure 9. The waveguiding effect of the corridor actually needs a separate modeling approach, however it has been included in our simulations to emphasize the variety of possible scenarios in a typical indoor environment.

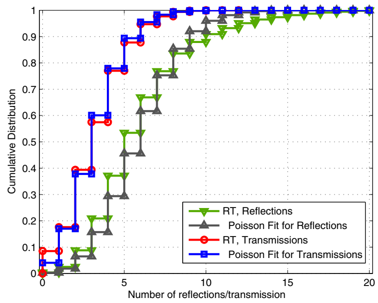

Fig. 8. CDFs for the Number of Reflections/Transmissions for Poisson Model vs RT data

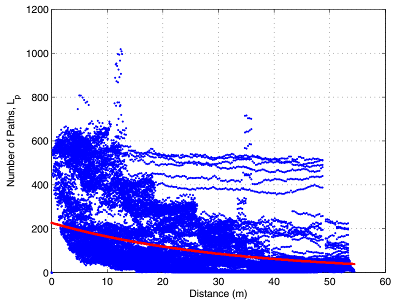

Fig. 9. Number of Paths (L_p) vs Distance

VI. Conclusion and Future Directions

In this paper, we have introduced a statistical multipath channel model based on ray optics. The model is based on an extensive database of RT simulations for a typical indoor environment. Important features of the CIR such as TOA, AOA, path gain and number of MPCs have been modeled. Modeling of these features is an important step in the development of precise indoor geolocation systems. Possible future research might include the verification of the proposed model with real-world measurements with finite bandwidth. Additionally, this method can be used to model the dynamic behavior of the indoor multipath channel.

Appendix

The two argument version of the tan^{-1} function, $atan2$, is defined as

$$atan2(y,x) = \begin{cases} tan^{-1}(y/x) & x > 0 \\ tan^{-1}(y/x) + \pi & x < 0, y \geq 0 \\ tan^{-1}(y/x) - \pi & x < 0, y < 0 \\ \pi/2 & x = 0, y > 0 \\ -\pi/2 & x = 0, y < 0 \\ undefined & x = 0, y = 0 \end{cases} \quad (14)$$

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