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SIGNAL DISTRIBUTION IN JOINT AOA-TOA DOMAIN IN INDOOR RF ENVIRONMENTS FOR PICO- AND FEMTO-CELL NETWORKS

Блауштейн Н. О. Розподіл сигналу в спільному часовому і кутовому просторі в різних середовищах всередині приміщень для піко-і фемтосотових систем. Представлені у статті результати досліджень показують, що ефективність обслуговування для кожного абонента, розташованого всередині та поза будівлею в піко- та фемтосотах залежить від точного передбачення розподілу потужності сигналу по кутах приходу та часу затримки. Це може бути досягнуто за допомогою пропонованого стохастичного підходу опису умов розповсюдження радіохвиль всередині та поза будівлею з врахуванням їх конфігурації (коридори, перетин коридорів, внутрішні кімнати), а також різних перешкод (меблі, обладнання, елементи архітектури і т.п.), розташованих навколо радіотраси, що з'єднує обидва термінали – передавач та приймач.

Ключові слова: АБОНЕНТ, ЕФЕКТИВНІСТЬ ОБСЛУГОВУВАННЯ, СТОХАСТИЧНИЙ ПІДХІД, СЕРЕДОВИЩЕ, ТЕРМІНАЛ

Блауштейн Н. А. Распределение сигнала в совместном временном и угловом пространстве в различных средах внутри зданий для пико- и фемто-сотовых систем. Представленные в статье результаты исследований показывают, что эффективность обслуживания каждого пользователя, расположенного внутри и вне зданий в пико- и фемтосотах, зависит от точного прогноза распределения мощности сигнала по углам прихода и временам задержки. Это может быть достигнуто с помощью предлагаемого стохастического метода описания условий распространения радиоволн внутри и вне зданий, с учетом их конфигурации (корридоры, пересечение корридоров, внутренние комнаты), а также различных препятствий (мебель, оборудование, элементы архитектуры, и т.п.), расположенных вокруг радиотрассы, соединяющей оба терминала – передатчик и приемник.

Ключевые слова: АБОНЕНТ, ЭФФЕКТИВНОСТЬ ОБСЛУЖИВАНИЯ, СТОХАСТИЧЕСКИЙ ПОДХОД, СРЕДА, ТЕРМИНАЛ

Blaunstein N. O. Signal distribution in joint AOA-TOA domain in indoor RF environments for pico- and femto-cell networks. The results of research submitted in the report have shown that the efficiency of service of each subscriber located in the indoor/outdoor picocell/femtocell environments depends on the precise prediction of signal power distribution in joint angle-of-arrival (AOA) and time-of-arrival (TOA) domains and that this can be achieved by using the proposed indoor-outdoor stochastic approach by accounting the environment configuration (single-corridor, crossing-corridors and inside-room radio propagation) as well as various obstructions (furniture, machinery, architecture elements etc.) located surrounding the radio path connected both terminal antennas, the transmitter and the receiver.

Key words: USER, SERVICE EFFICIENCY, STOCHASTIC APPROACH, ENVIRONMENT, TERMINAL.

I. Introduction. Increasing demand for wireless communication systems in the past decades, recent standardization of pico- and femto access points (FAP) deployed in indoor environments, availability of the 4-G mobile broadband technologies for indoor environments, incorporation of the self-organized networks (SON) algorithms into the optimization techniques of the 4-G mobile services all require significant research investments in areas of high data rate communications over the wireless broadband multiple-input-multiple-output (MIMO) media. A detailed knowledge of radio propagation conditions inside buildings is critical for efficient design of indoor communication systems [1]. Many current models address only the path-loss behaviour of indoor channels. Implementations of the 4-G broadband technologies for FAP indoor environments, as well as growing number of base stations (BS) and mobile subscribers (MS) with the MIMO capabilities have motivated the renewed interest in accurate channel modelling not only in range domain, but also in the time-of-arrival (TOA) and angle-of-arrival (AOA) domains.

Therefore, detailed knowledge of radio propagation conditions inside buildings is critical for efficient design of indoor-outdoor (i.e., femto) and indoor-indoor (i.e., pico) communication systems. Current models mostly address the path-loss behavior of indoor channels. Implementations of the 4-G broadband technologies for pico-cell and femto-cell indoor-outdoor environments, as well as, growing number of subscribers working with portable multi-beam antennas, have motivated the renewed interest for accurate channel modeling not only in the space (along the radio path), but also in the time-of-arrival (TOA) and angle-of-arrival (AOA, azimuth and elevation) domains, mostly for multiple-input-multiple-output (MIMO) access servicing by using so-called multi-beam or phased-array adaptive antennas [1, 2].

In this work, the statistical multi-parametric approach that was originally proposed for the outdoor urban environment and was approbated by numerous experiments carried out for various elevations of base station (BS) and mobile subscriber (MS) antennas with respect to building surrounding, is adopted for modeling the indoor propagation conditions [1]. The key in the proposed model is representation of the RF propagation conditions in the indoor environment as a) LOS propagation within the indoor corridor, room or hall, and b) NLOS propagation determined by obstacles between these indoor spaces. The derived model relies on the observations that the majority of the RF energy in the indoor environment is dissipated through the LOS propagation in corridors characterized by a waveguide effect, and the NLOS propagation between the corridor and the adjacent rooms via indoor openings.

II. Modified Stochastic Multi-Parametric Approach. In this Section, we present the stochastic model developed in [1, 3] for different outdoor communication links and various scenarios occurring there, which then had been adapted for indoor environment conditions in [1]. Thus, this model was generated and combined with the statistical waveguide model [4] where several results of path loss and fading prediction in indoor environments were presented, but only for signal power distribution in the space domain along radio path between the transmitter and the receiver. To fully describe the mechanism of multiple scattering and multi-reflections with guiding effects of corridors, we account for two distributions in such a combined stochastic model as was done in [1].

The *first* distribution, $\mu(\mathbf{r},\varphi)$ describes the distribution of multiple scattered waves in the space (defined by the 3-D vector **r**) and AOA domains, that is, it describes the general spatial distribution of obstructions-scatterers. As was shown in [1-3], a joint spatial-temporal distribution of waves $\mu(\mathbf{r},\varphi)$ can be arranged as a joint AOA and TOA distribution, $\mu(\tau,\varphi)$, It can be presented for $\gamma_0 r >> 1$ and in the case of $z_1 < \overline{h} < z_2$ as [2]:

$$\mu(\tau,\varphi) = \mu_1 + \mu_2 = 0.5\nu \sin^2(\alpha/2)\left\{\gamma_0 \overline{h}\,\frac{d^2(\tau^3-\tau)}{2(\tau-\cos\varphi)}\right\} f_1(\tau,\varphi)$$
$$+\,0.5\nu \sin^2(\alpha/2)\left\{(z_2-\overline{h})\frac{d(\tau^2-2\tau\cos\varphi+1)}{2(\tau-\cos\varphi)} f_2(\tau,\varphi)\right\} \qquad (1)$$

For the case of $z_1, z_2 < \overline{h}$ expression (1) can be reduced to

$$\mu(\tau,\varphi) = 0.5\nu\gamma_0 \cdot \sin^2(\alpha/2)\cdot \tau d \cdot \exp\{-\gamma_0 \tau d\}. \qquad (2)$$

Here: $$f_1(\tau,\varphi) = \exp\left[-\gamma_0\left(\frac{d\tau^2(z_2+\overline{h}) - 2d\tau z_2\cos\varphi + d(z_2-\overline{h})}{2z_2(\tau-\cos\varphi)}\right)\right]/z_2, \qquad (3a)$$

$$f_2(\tau,\varphi) = \exp\left[-\gamma_0\frac{d(\tau^2-2\tau\cos\varphi+1)}{2(\tau-\cos\varphi)}\right]/\overline{h}. \qquad (3b)$$

In all the expressions above, λ denotes the wavelength of the transmitted signal, $\overline{h}$ is the average height of walls and doors, z_1 and z_2 are the heights of the transmitter and receiver antennas, respectively, φ is the angle of multipath components of the total field in the horizontal plane (i.e., azimuth) arriving at the receiver after multiple scattering from the buildings surrounding both the transmitter and the receiver, α is the angle between lines to the receiver and to the transmitter, and

d is the distance between the terminal antennas, *Rx* and *Tx*, in meters. Here also the parameter of obstruction contours' density, $\gamma_0 = 2\bar{L}\nu/\pi$, is introduced, with $\bar{L}$ denoting the average obstructions' length and ν denoting the number of obstructions per $10m^2$.

The *second* distribution function is $\mu(r,\varphi)$ which describes a probability of the wave modes existence caused by a multi-slit (slit are the gapes between walls lining the corridor) waveguide at distance r from the transmitter. We assume that the angle φ takes discrete values with a resolution of degrees. Finally, we get according to [4]:

$$\mu(r,\varphi)_{wg} = \exp\left[-2\frac{|\ln\chi|}{a'(\varphi)}\cdot r\right]. \tag{4}$$

Here $\chi = \bar{L}/(\bar{L}+\bar{l})$ is the brokenness parameter along the corridor, a is the corridor width, $\bar{L}$ and $\bar{l}$ are the average length of screens (walls) and slits (gaps between rooms and intersections of corridors), respectively, and r is the transmitter-receiver distance. The definition of $a'(\varphi)$ is given below.

Thus, the completed form of the joint AOA and TOA distribution of scatters can be written as [1]:

$$\mu_f = \mu(r,\varphi)\cdot\mu(r,\varphi)_{wg} \tag{5}$$

Substituting the appropriate expressions for $\mu(\tau,\varphi)$ and $\mu(\tau,\varphi)_{wg}$, we can rewrite (5) in the extended form by accepting the density function of all single scatterers as a function of τ and φ [1, 4]:

$$\mu_f(\tau,\varphi) = 0.5\gamma_0\nu\sin^2(\alpha/2)\tau d\exp\{-\gamma_0\tau d\}\exp[-2\frac{|\ln\chi|}{a'(\varphi)}\cdot\frac{d(\tau^2-1)}{2(\tau-\cos\varphi)}]. \tag{6}$$

Equation (6) is valid for the typical urban situation when both, the receiver and transmitter, are placed below the salling level. Here $a'(\varphi) = a\sqrt{\frac{4a^2}{\lambda^2 n^2}+1}$, where n is the number of reflections from walls (number of waveguide modes), and $a' = 2a^2/(\lambda n)$ for $a > \lambda$. It was shown in [4], for distances far from the source, only the main waveguide modes (with n=1,2) propagate without any attenuation within the street waveguide.

We define the discrete spectrum of the total signal power within a broken corridor waveguide taking into account the geometry presented in [1, 4] as:

$$W_{wg}(\tau,\varphi) = W_0\frac{2(\tau-\cos\varphi)}{d(\tau^2-1)}\exp\left[-2\frac{|\ln\chi|}{a'(\varphi)}\cdot\frac{d(\tau^2-1)}{2(\tau-\cos\varphi)}\right], \tag{7}$$

where W_0 is a signal power of the antenna in direction of direct visibility (LOS component). Now to find the total signal power distribution, in time and azimuth domains, and accounting for guiding street effects, we need to combine expressions (1) and (7), yielding

$$W_{fin}(\varphi,\tau) = W_0\cdot\mu(\varphi,\tau)\cdot W(\varphi,\tau)_{wg} \tag{8}$$

to determine the joint 2-*D* distribution in the AOA and TD domains, respectively.

We use for numerical simulation the following expression, which describes the distribution of the normalized power (with respect to signal power in free space) in the joint azimuth-time domain along the corridor in NLOS conditions versus distance between the transmitter and the receiver antenna d and the real time $t = d\cdot\tau/c$:

$$w(t,\varphi) = \frac{W(t,\varphi)}{W_0} = \gamma_0\cdot\nu\cdot\sin^2(\alpha/2)\cdot c\cdot t\cdot\exp\{-\gamma_0 c\cdot t\}\frac{(c\cdot t/d-\cos\varphi)}{d\left((c\cdot t/d)^2-1\right)}\exp\left[-2\frac{|\ln\chi|}{a'(\varphi)}\cdot\frac{d\left((c\cdot t/d)^2-1\right)}{2\left((c\cdot t/d)-\cos\varphi\right)}\right] \tag{9}$$

This formula was used for numerical analysis of radio propagation in indoor links.

III. Experiments. ***Description of the Experiments Site.*** The experiments carried out in indoor environments of campuses Ben-Gurion University of the Negev. Above we see the map of floor number 4, the paths and the points where we made the experiments. We putted the transmitter antenna beside office 417 – the white quadrate at the left-side of the map (see Fig. 1). The angle $\varphi = 0^0$ shows the direction (radio path) along the corridor corresponding to LOS conditions; the direction upward follows to angle $\varphi = -90^0$ and the direction downward follows to angle $\varphi = +90^0$. The corresponding radio paths of the experiments are presented by blue continuous lines. Red points along each radio path (e.g., along each blue line) represent the points where we sample the received signals of the experiments. The transmit antenna is fixed directional antenna with height 1.2 meter and the received antenna is mobile directional antenna with height ~ 1.2 meter.

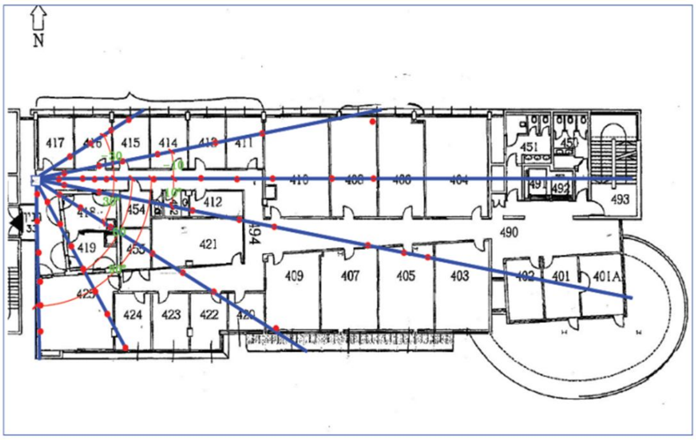
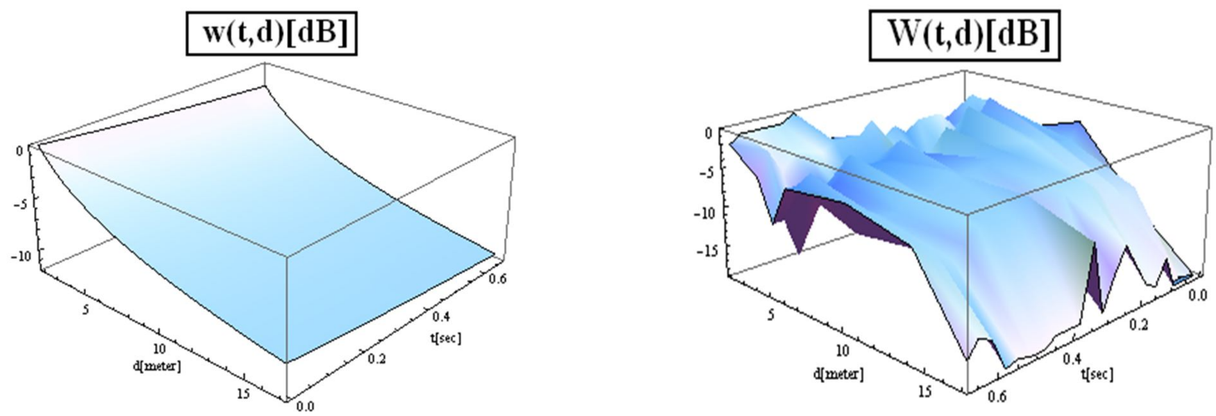


Fig. 1. Topographic map of the experimental site

We measured the signal power distribution over the whole floor, and we sampled the received energy in all positions of radio paths denoted by red points at the above map. The transmitting signal power was 4*dBm*; the carrier frequency is *f*= 2.457*GHz*.

IV. Comparison with Experimental Data in LOS and NLOS conditions

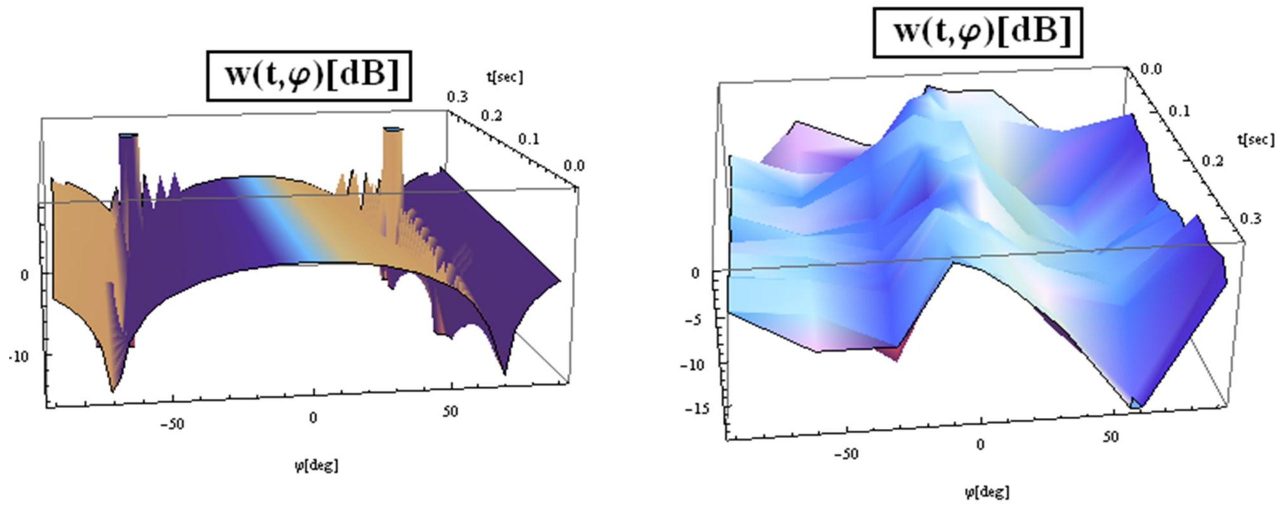
4.1. Experiment number 1 – LOS conditions along the corridor. In this experiment measurements were carried out along the corridor in LOS conditions (as seen from Fig. 1); the length of the Corridor is 17 meters. We measured the signal power distribution at the receiver antenna along the corridor at each point from 1 meter to 17 meters from the transmitter antenna and signal was recorded at the receiver by a special program every 0.033 second at each point with the received signal period 0.66 second. The corresponding formula for computation is (7). Below, we plot in Figure 2 $w(t,d)$ ([dB]) along the corridor for φ=0, χ=0.9, a corridor width a=2m.



(a) (b)

Fig. 2: 3D plot of $w(t,d)$ vs. t and d for φ=0, χ=0.9: (a) theory, (b) experiment.

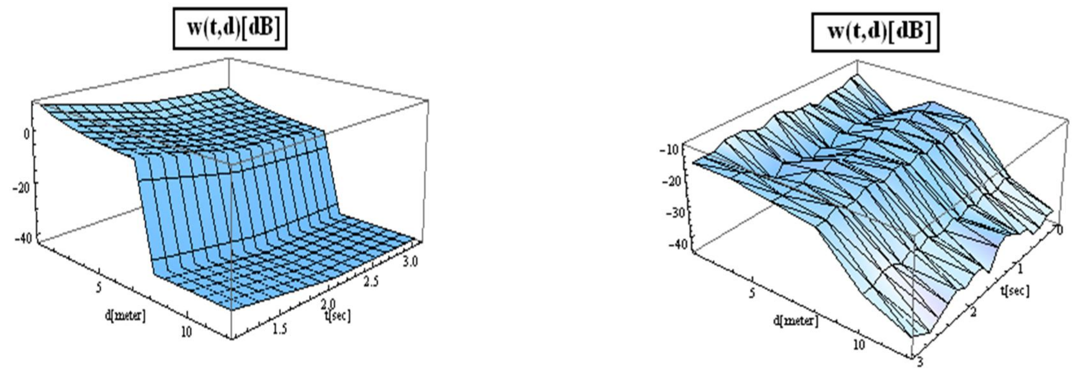
4.2. Experiment number 2 – LOS conditions along the corridor. In this experiment along the corridor with LOS conditions, we measured and calculated according to (7) the received signal power distribution at different distances of 2, 4, 5, 6, 10, 14, and 17 meters from the transmitter antenna for different azimuth directions defined by the angle φ. For these purposes, we rotated the receiver antenna with hopes of ~ 10 deg in each angle with the period of 0.33 second. We plotted graphs of $w(t,\varphi)$ in [dB] along the corridor, when d=const, φ=[-90 , 90], χ =0.9, and a is 2 meter (see Fig. 3).



(a) (b)

Fig. 3. 3D plot of $w(t, \varphi)$ vs. t and φ for d=10m, χ=0.9: (a) theory, (b) experiment

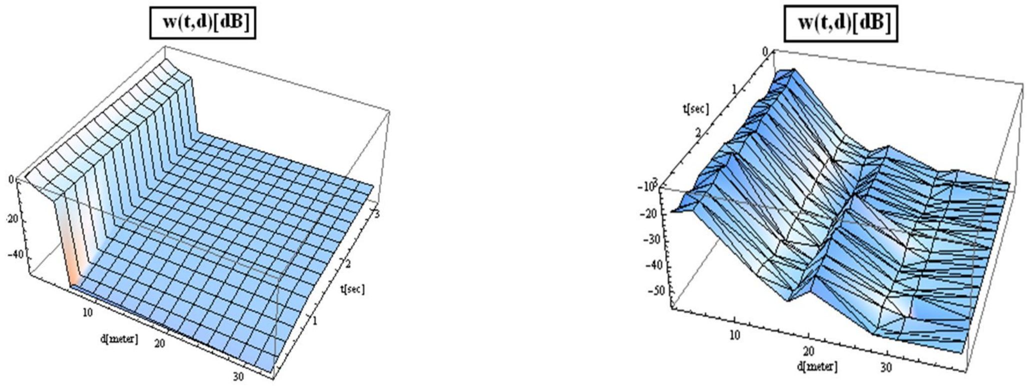
4.3. Experiments number 3 - NLOS conditions inside rooms lining the corridor. In this experiment we measured the received signal power distribution at different angles at (90, 60, 30, 10, 0, -10, -30) degrees of the rotated transmitter antenna. We sampled the received signal at deferent distances from the transmit antenna d, and at each distance d, we recorded the received signal power with the period 3 seconds. The corresponding computations according to (9) are presented in Fig. 4 and 5.



(a) (b)

Fig. 4. 3D graphs of $w(t, d)$ in[dB] between the rooms for φ=90 [deg], t=[0, 3]sec, d= [0,12] m.
(a) theory, (b) experiment

From above comparison one can see that results of theoretical prediction based on formula (7) for LOS conditions along the corridor and on formula (9) for NLOS conditions inside rooms, as shown by Figs. 3 to 5, can be used as a good predictor of the signal power distribution in joint AOA-TOA, distance-TOA and distance-AOA domains for most directions of the main antenna loop. At the same time, the results of theory look smooth with respect to rough view of measurement data. This difference can be explained by a lot of small roughness and obstructions of walls and a complicated geometry of the rooms and their orientation with respect to the corridor that observed really according to topographic plan presented in Fig. 1, and that finally resulting such a complicated picture.



(a) (b)

Fig. 5. 3D graphs of $w(t, d)$ in[dB] between the rooms for φ=10 [deg], t=[0, 3]sec, d= [0, 33] m.
(a) theory, (b) experiment.

Summary. The joint AOA-TOA distribution for indoor corridor and crossing corridors accompanied with rooms lining each corridor, which consists various obstructions (furniture, machinery, architecture elements etc.) was derived in this work. The accuracy of the proposed model was validated using the collected measurements, both for access point located inside and outside the building. The separate and the joint AOA-TOA measurements were obtained via a time-domain based data collection method and highly directive parabolic antennas. The obtained results, both theoretically and experimentally, allowed us to summarize the following:

– The proposed stochastic combined indoor-outdoor model allows designers of pico-cell and femto-cell networks to obtain precise signal power distribution in joint AOA-TOA domain that was proved by the corresponding experiments carried out in different indoor environments: along and across corridors, inside rooms etc.

– The proposed approach allows increasing of grade-of-service (GoS) and quality-of-service (QoS) minimum per twice by using multi-beam adaptive antennas, which will operate in joint AOA (azimuth and elevation) and TOA domains, for precise positioning of each subscriber located in areas of service in pico-cell and femto-cell environments.

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