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Ray-Optical Modeling of Simulcast Radio Propagation Channels in Tunnels

Y. P. Zhang and H. J. Hong

Abstract—Simulcast radio propagation channel characteristics inside tunnels are considered in this paper. Based on the image theory of ray optics, a simulcast radio propagation channel in a rectangular tunnel is exactly formulated. As only the field components of horizontal and vertical polarization are of interest in real implementation, the exact formulation is approximated to facilitate the numerical computation. The calculated simulcast radio propagation channels are comparable fairly to measurements at 900 MHz and 2.0 GHz. The validated ray-optical modeling approach is then applied to simulate simulcast radio propagation channel characteristics at 900 MHz and 2.0 GHz to gain deeper insight and better understanding of this type of channels in tunnels. Results show that large fluctuations occur in the capture regions of the distributed antennas for both 900 MHz and 2.0 GHz. The fluctuations in the simulcast regions are larger at 2.0 GHz than at 900 MHz. The root-mean-squared (rms) delay spread is greater in the simulcast regions than in the capture regions of the distributed antennas. This larger delay spread is mainly due to the delay introduced by the transmission medium. Large values of the rms delay spread can be avoided by a careful design of the distance between the distributed antennas.

Index Terms—Distributed antenna systems, mobile communications, ray-optical modeling of radio propagation, tunnels.

I. INTRODUCTION

TO EXTEND public land mobile telephone systems into tunnels the most serious factor to contend with has been the fundamental reality that radio signals do not penetrate into and radiate out of such environments effectively [1]. At a lower frequency, e.g., 450 MHz, radio signals also cannot propagate well inside tunnels and they suffer large attenuation. The traditional solution to this problem is to guide radio signals artificially by means of leaky coaxial cables that have to be installed throughout tunnels [2]. At a higher frequency, e.g., 900 MHz, the propagation of radio signals becomes improved and they can propagate naturally well inside tunnels. Thus, radio coverage of tunnels by discrete antennas has been attempted [3]. The leaky coaxial cable solution delivers uniform radio coverage but it becomes rather expensive for systems operating at higher carrier frequencies and it involves maintenance at regular intervals. In addition, it is quite cost intensive to install them after tunnels have been opened to the traffic. On the other hand, the discrete antenna solution is more economical. Discrete antennas can be

easily and quickly installed and maintained but they cannot deliver uniform coverage. Also their coverage distances are often insufficient for long tunnels. Furthermore, the radio signals originated from discrete antennas are susceptible to the blockage from sizable vehicles; as a result, an additional fading margin must be introduced. To overcome the problems associated with the existing solutions and to meet future needs, the distributed antenna solution has been proposed [4]. The distributed antenna solution is based on the flexible combination of cheap transmission media with antennas to realize a single-cell or multiple-cell mobile radio communication network. An attractive feature of the distributed antenna solution is the possibility to use the transmission media that have already been installed for other purposes. An interesting property of the distributed antenna solution is that the propagation of radio signals is different from a capture region to a simulcast region. The capture region is the area where the power transmitted from one antenna dominates, while the simulcast region is the area between the two antennas where neither power from each antenna dominates. The distributed antenna solution to tunnel radio coverage is described in Section II. The radio propagation channels excited by the distributed antennas are formulated in Section III. The measured and simulated radio propagation channel characteristics are analyzed and discussed in Section IV. Section V summarizes the conclusions.

II. DISTRIBUTED ANTENNA SYSTEMS

The principle of using a distributed antenna system to cover a tunnel is to subdivide the tunnel into multiple shorter sections and let each antenna cover one short section [5]. A generic distributed antenna system consists of a signal source, a transmission medium, and multiple antennas. Depending on the frequency of the signals being transmitted over the medium and the requirement of the mobile telephone system capacity, the medium may be a twisted pair or a coaxial cable. For the twisted-pair distributed antenna system the signal source codes voice and data signals for example in ADPCM digital format and complies digitized voice and data signals as the standard E1 trunk 2.048 Mb/s. Assuming that 64 kb/s is for the signaling channel, a total number of 60 voice channels can be supported. The number of time-slots assigned to an antenna is configured according to the number of RF channels provided by the circuitry of the distributed antenna [5]. The separation between two adjacent distributed antennas can be up to 1.6 km. Based on the digital cordless phone common air interface at 900 MHz, a twisted pair distributed antenna system covering distances longer than 4 km has been demonstrated [6]. For the coaxial cable distributed antenna system the signal source directly injects modulated RF signals

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Fig. 1. Illustration of ray-optical modeling of simulcast radio propagation channels.

to the antennas tapped on the coaxial cable. The coverage of the coaxial cable distributed antenna system depends on the loss through the coupled portion of an antenna tap, the gain of the antenna on the coaxial cable fed from the tap, the loss from the antenna on the coaxial cable to the worst case position of a mobile radio, and the margin required to meet the link quality. To compensate for transmission loss in RF signal power inside the coaxial cable, bidirectional amplifiers need to be inserted at intervals along the coaxial cable. Though the ideal coaxial cable distributed antenna system would have cable sections of equal length and loss; tunnel restrictions for locating the cable, amplifiers, and antennas rarely make this possible.

For the aforementioned distributed antenna systems, the simulcast technique is often employed in coalmines or some tunnels where high-capacity mobile communication services are not required, while on the other hand, the frequency reuse technique has to be utilized in underground metropolitan cities or mass rapid transit tunnels where high-capacity services are expected. To implement distributed antenna systems, the modeling of simulcast radio propagation channels is absolutely essential in maximizing coverage distance, minimizing radiated power, path loss, far-field interference, and susceptibility to uplink interference and is also definitely useful in characterizing the cochannel interference for frequency reuse distributed antenna systems. Surprisingly, little work has been done to develop radio propagation channel models for distributed antenna systems [7] although extensive effort has been devoted to model radio propagation channels excited by a discrete antenna

or a leaky coaxial cable in tunnels [8]–[18]. In the next section, we will formulate a simulcast radio propagation channel model based on the image theory of ray optics.

III. FORMULATION OF SIMULCAST RADIO PROPAGATION CHANNEL MODEL

Ray-optical modeling of radio propagation channels in urban and indoor environments has been a subject of active research since the last decade [19], [20]. Ray-optical modeling of radio propagation channels in tunnel environments can be traced back to as early as 1970s when Mahmoud and Wait derived a geometrical ray model for straight rectangular tunnels, taking into account the coupling between the horizontally and vertically polarized rays [8]. They found, however, that this coupling could be neglected if only the field components of major polarization are of interest. Zhang and Hwang extended the ray-optical approach to branched tunnels [13], [14] and Didascalou *et al.* to arbitrarily shaped tunnels [15], [16]. Chen and Jeng considered the effects of traffic vehicles in tunnels [17] and Pallares *et al.* the transition from land propagation to tunnel propagation [18].

A. Hertz Potentials

Here we consider the general case of a simulcast radio propagation channel in a rectangular tunnel as shown in Fig. 1. The fields can be obtained from any two suitable scalar potentials. Based on the problem to be solved, we choose Π_x , Π_y as two

scalar functions, where Π_x and Π_y are x and y components of Hertz electric vectors, respectively, [8]. They are given by

$$\begin{aligned} & \begin{bmatrix} \Pi_x(x, y, z) \\ \Pi_y(x, y, z) \end{bmatrix} \\ &= \frac{1}{4\pi i \omega \epsilon_o} \sum_m \sum_l \sum_j \left[\frac{\exp(-ik_o r_{ljm} - ik_o \sqrt{\epsilon_c} z_{m1})}{r_{ljm}} \right] \\ & \times [M_{ljm}] \begin{bmatrix} S_{xm} \\ S_{ym} \end{bmatrix} \end{aligned} \quad (1)$$

where $\omega, \epsilon_o, \epsilon_c, \kappa_o, i$ have the customary meaning, S_{xm} and S_{ym} are the horizontal and vertical moments of the m th distributed antenna located at (x_m, y_m, z_m) , z_{m1} is the cable length between the m th distributed and the first distributed antennas, l and j are integers representing the multiple images of the m th distributed antenna and the m th distributed antenna itself in any arbitrary manner, M_{ljm} is the product of the reflection coefficients of the images taking into account the coupling between the horizontally and vertically polarized rays. Equation (1) is an exact equation provided that the geometrical ray approximation is valid and the m th distributed antenna is an infinitesimally short dipole or a point source. For the m th distributed antenna of finite length L_m located on the x -axis, the horizontal moment S_{xm} can be expressed as

$$S_{xm} = I_m L_m \quad (2)$$

where I_m is the current and L_m should be much smaller than the wavelength λ . Similarly, we can find S_{ym} for the case of the m th distributed antenna located on the y -axis. r_{ljm} , the distance from the $(l - j)$ image of the m th distributed antenna to the receive antenna, is given by

$$r_{ljm} = \sqrt{(z_r - z_m)^2 + (x_r - x_l)^2 + (y_r - y_j)^2}. \quad (3)$$

(x_r, y_r, z_r) are the coordinates of the receive antenna and (x_l, y_j, z_m) are the coordinates of the $(l - j)$ image of the m th distributed antenna, where

$$x_l = 2uw \pm x_m, \quad u = -\infty \text{ to } \infty, \quad (4)$$

$$y_j = 2vh \pm y_m, \quad v = -\infty \text{ to } \infty. \quad (5)$$

In the above, w and h are the width and height of the tunnel, respectively. The infinity u and v must be truncated in the numerical computation. Basically, the smaller the tunnel dimensions w and h are and the lower the frequency is, the smaller u and v are needed for the convergence of computation. If only the field components of major polarization are of interest, the

coupling between the horizontally and vertically polarized rays can be neglected. As a result, (1) is approximated as

$$\begin{aligned} & \begin{bmatrix} \Pi_x(x, y, z) \\ \Pi_y(x, y, z) \end{bmatrix} \\ &= \frac{1}{4\pi i \omega \epsilon_o} \sum_m \sum_l \sum_j \left[\frac{\exp(-ik_o r_{ljm} - ik_o \sqrt{\epsilon_c} z_{m1})}{r_{ljm}} \right] \\ & \times \begin{bmatrix} R_H^{n_{lm}} \cdot R_V^{n_{jm}} \\ R_V^{n_{lm}} \cdot R_H^{n_{jm}} \end{bmatrix} \begin{bmatrix} S_{xm} \\ S_{ym} \end{bmatrix} \end{aligned} \quad (6)$$

where R_H and R_V are the Fresnel reflection coefficients for horizontal and vertical polarizations, respectively, n_{lm} and n_{jm} are the numbers of reflection on the vertical and horizontal tunnel walls, respectively, involved in forming the $(l - j)$ image of the m th distributed antenna.

B. Electric Field

The respective horizontal and vertical electric field components are then obtained as follows:

$$E_x(x, y, z) = \left(k_o^2 + \frac{\partial^2}{\partial x^2} \right) \Pi_x + \frac{\partial^2 \Pi_y}{\partial y \partial x} \quad (7)$$

$$E_y(x, y, z) = \left(k_o^2 + \frac{\partial^2}{\partial y^2} \right) \Pi_y + \frac{\partial^2 \Pi_x}{\partial x \partial y}. \quad (8)$$

C. Power

Modern RF equipment measures radio signal strength in power. The distributed antennas are often directional antennas. Knowing that the m th distributed antenna radiates P_{tm} power in the tunnel space and considering its gain and directivity, the received power by the receive antenna for horizontal and vertical polarization can be expressed as

$$\begin{aligned} & \begin{bmatrix} P_{rH} \\ P_{rV} \end{bmatrix} = \left(\frac{\lambda}{4\pi} \right)^2 \\ & \times \left| \sum_m \sum_l \sum_j \left[\frac{G_{ljm} \exp(-ik_o r_{ljm} - ik_o \sqrt{\epsilon_c} z_{m1})}{r_{ljm}} \right] \right. \\ & \times \left. \begin{bmatrix} R_H^{n_{lm}} \cdot R_V^{n_{jm}} \\ R_V^{n_{lm}} \cdot R_H^{n_{jm}} \end{bmatrix} \sqrt{P_{tm}} \right|^2 \end{aligned} \quad (9)$$

where G_{ljm} is the product of the m th distributed antenna and receive antenna field amplitude radiation patterns corresponding to the path originated from the $(l - j)$ image of the m th distributed antenna. Equation (9) is valid for rectangular tunnels and can also be applied to arched tunnels. The method of finding the locations of the images of the antenna in arched tunnels can be found in [17].

$$[\tau_{rms}] = \sqrt{\frac{\sum_m \sum_l \sum_j P_{rljm} \tau_{ljm}^2}{\sum_m \sum_l \sum_j P_{rljm}} - \left(\frac{\sum_m \sum_l \sum_j P_{rljm} \tau_{ljm}}{\sum_m \sum_l \sum_j P_{rljm}} \right)^2} \quad (10)$$

D. Time Delay

One potential problem of a distributed antenna system is the delay spread introduced by the cable and the multiple antennas. This limits the maximum data rate that the system can support. A rough guideline to determine the maximum signal bandwidth is the coherence bandwidth, which can be computed from the rms delay spread by the formula $1/2\pi\tau_{\text{rms}}$ where τ_{rms} is the rms delay spread. It can be computed by (10), as shown at the bottom of the previous page, where τ_{ljm} is the excess time delay and P_{rljm} is the received power from the ray originated from the $(l-j)$ image of the m th distributed antenna. τ_{ljm} is given by

$$\tau_{ljm} = \frac{\sqrt{\varepsilon_c} z_{m1}}{c} + \frac{r_{ljm}}{c} - \frac{r_{001}}{c}. \quad (11)$$

P_{rljm} is expressed for horizontal polarization as

$$P_{rljm} = \left(\frac{\lambda}{4\pi}\right)^2 \times \left| \left[\frac{G_{ljm} \exp(-ik_o r_{ljm})}{r_{ljm}} \right] [R_H^{n_{lm}} \cdot R_V^{n_{jm}}] \sqrt{P_{tm}} \right|^2 \quad (12)$$

and for vertical polarization as

$$P_{rljm} = \left(\frac{\lambda}{4\pi}\right)^2 \times \left| \left[\frac{G_{ljm} \exp(-ik_o r_{ljm})}{r_{ljm}} \right] [R_V^{n_{lm}} \cdot R_H^{n_{jm}}] \sqrt{P_{tm}} \right|^2. \quad (13)$$

The simulcast radio propagation channel model developed above suffers from the weakness of geometrical optics but no alternative way of solving excitation problems in tunnels has yet been proposed. Nevertheless, it still reveals some important propagation characteristics of the simulcast radio propagation channels in tunnel environments.

IV. RESULTS AND DISCUSSION

For validation purposes measurements have been made. In what follows the measurements are first described, and then the comparisons of the simulations with the measurements are presented. Finally the simulated results of simulcast radio propagation channels are discussed.

A. Experimental Validation

The measurements of the twisted-pair distributed antenna system were made in a corridor. The corridor is 3.83 m high, with a suspended tile false ceiling at 2.83 m, and 2.8 m wide. The ceiling and the floor of the corridor are reinforced concrete and the walls are brick. The system employed two HP 44233B signal generators and two monopoles as the distributed transmitters, an HP 8563E spectrum analyzer and a monopole as the receiver, and a personal computer as the data collector. Two distributed monopoles were installed in the corridor in a height of 1.6 m below the false ceiling and at a distance of 0.3 m from the left wall. Their separation distance was 30 m.

The measurements of the coaxial cable distributed antenna system were made in a tunnel. The tunnel is reinforced concrete with the height of 8 m and the width of 6 m. The system was

an HP 8753D network analyzer: Port 1 of the network analyzer used as the transmitter; Port 2 utilized as the receiver; and the built-in disk driver employed as the data collector. The system was operated at the central frequency of 2.0 GHz with frequency spectrum over the range of 400 MHz, which yields an equivalent resolution of 2.5 ns and a repetition period of 500 ns in the time domain. Two slot arrays were constructed on the external conductor of the coaxial cable as two transmit antennas for the measurements in the tunnel. The slot array close to the transmitter was referred to the first slot array. The coaxial cable was installed 1.48 m high from the floor and 0.48 m away from the left wall of the tunnel. The separation distance between two adjacent slot arrays was 25 m. The receive antenna was a broadband discone antenna.

We divided our measurement efforts into two distinct categories: 1) dynamic narrowband measurements, we measured received signal power along the longitudinal direction of the corridor when the receiving antenna in a height of 1.5 m above the floor was being moved at a constant speed together with the receiver and data collector housed on a trolley; 2) static wideband measurements, we measured multipath impulse responses when the receiving antenna was stationary also at the height of 1.5 m above the floor. Measurements were taken on a cluster scale with the cluster having a size of 16 cm². The adjacent cluster on a route either parallel or radial to the cable was 1 m apart for most measurements. Four individual impulse responses were obtained for each cluster. Each individual impulse response was measured over several hundred microseconds. They were then averaged at each time delay to yield an averaged impulse response.

Fig. 2 shows the comparison of the measured and simulated received signal levels of vertical polarization at a distance of 1.4 m from the left wall of the corridor for the frequencies at 900 MHz and 2.0 GHz. To quantify the agreement of simulations and measurements, mean values and standard deviations of the difference in dB between the measured and simulated received signal levels are determined. The small mean error 0.32 dB and standard deviation 4.53 dB indicate the good performance of the model for the case of 900 MHz. The increased mean error and standard deviation for the case of 2.0 GHz can be explained by our measurement limitation. It was found that there was a frequency-drifting problem in one HP 44233B signal generator at 2.0 GHz. To combat this problem a broad frequency span was employed in our receiver. Thus, the measured received signal was not a truly simulcast signal. This can be seen from the shallow fading in the simulcast region (a short section in the middle area between two transmit antennas). On the contrary, the simulated received signal is a truly simulcast signal that displays the deep fading in the simulcast region. The different fade depths in the simulcast region between the measured and simulated received signal levels account for the increased discrepancy.

Fig. 3 shows the comparison of the normalized measured and simulated power delay profiles at a distance of 3 m from the left wall of the tunnel at 2.0 GHz. They agree reasonably. Many echoes are predicted and correlated with the multipath propagation structure by the model and experimentally verified as

Fig. 2. Calculated and measured received signal levels versus distance in the corridor. (a) at 900 MHz. (b) at 2.0 GHz.

having the correct delays. The first group of echoes before excess delay 25 ns is from the slot array closer to Port 1 of the network analyzer and the second group around 200 ns from the slot array far away from port 1. The echoes that occur from excess delay 25 ns to 165 ns are related with the multiple reflections from the walls of the tunnel. The first group of echoes is stronger than the second group of echoes in Fig. 3(a). On the contrary, the second group of echoes has an even higher power than the first group of echoes in Fig. 3(b). This is because the receive antenna was closer to the first slot array for Fig. 3(a) and to the second slot array for Fig. 3(b). The measured root mean square (rms) delay spread values for the two profiles are 64 and 69 ns while the simulated rms delay spread values are 60 and 62 ns.

B. Simulcast Radio Propagation Channel Characteristics

Having validated the simulcast radio propagation channel model, we now use it to study hypothetical simulcast radio links at 900 MHz and 2.0 GHz in a tunnel in order to gain deeper

Fig. 3. Calculated and measured power delay profiles in the tunnel at 2.0 GHz. (a) Close to the first slot array. (b) Close to the second slot array.

insight and better understanding of the simulcast radio propagation channels. The tunnel is assumed to have the following dimensions: width = 9 m, height = 5 m, and length = 1000 m. Depending on the methods and materials used to construct the tunnel, the dielectric constant ϵ_r and the conductivity σ of the tunnel walls may vary from 5 to 10 and from 0.01 to 0.1 S/m. We choose $\epsilon_r = 10$ and $\sigma = 0.01$ S/m in our study. The distributed monopole antennas are fixed at (2.5, 4.5, 0), (2.5, 4.5, 500), and (2.5, 4.5, 1000), respectively. They are linked with an RF coaxial cable that has a typical dielectric medium of $\epsilon_r = 1.32$. The receive monopole antenna is being moved along the longitudinal direction at (4.5, 2.5, z) into the capture and simulcast regions. Fig. 4 shows the received signal levels for the case of the three distributed antennas radiating the same power to the tunnel. The same radiated power implies that the coaxial cable transmission loss is compensated with in-line amplifiers. As shown, large fluctuations occur in the capture regions of the distributed antennas for both 900 MHz and 2.0 GHz. The fluctuations in the simulcast regions are larger at 2.0 GHz than at 900 MHz. Fig. 5 shows the rms delay spread

Fig. 4. Received signal levels versus distance for the case of the three distributed antennas radiating the same power to the tunnel. (a) 900 MHz. (b) 2.0 GHz.

for the case of the three transmit antennas radiating the same power to the tunnel. Note that the rms delay spread is greater in the simulcast regions than in the capture regions of the distributed antennas and the rms delay spread is the largest in the first simulcast zone (region between the first and second distributed antennas from the signal source). This is due to the multipath rays of significant amplitude arriving at the simulcast zone from the furthest distributed antenna. For the subsequent simulcast zones, the delay-spread values are smaller due to the fact that the mean delay of the rays from the furthest antenna decreases. Also note that the rms delay spread is independent of the frequency, which is believed due to the result of the compensated coaxial cable transmission loss for this case.

Fig. 6 shows the received signal levels for the case of the three distributed antennas radiating different power to the tunnel. The different radiated power implies that coaxial cable transmission loss is uncompensated. Note that the distributed antenna of the 900-MHz simulcast system at 1000 m still makes noticeable fluctuations to the received signal power within its vicinity, but no similar effect can be seen for the 2.0-GHz simulcast

Fig. 5. RMS delay spread versus distance for the case of the three distributed antennas radiating the same power to the tunnel. (a) 900 MHz. (b) 2.0 GHz.

system. This is because the 2.0-GHz simulcast system suffers from a greater signal loss due to the higher attenuation constant in the coaxial cable at higher frequencies (4.4 dB/100 m at 900 MHz and 6.5 dB/100 m at 2.0 GHz). The fluctuations diminish down the tunnel because the rays with multiple reflections from the furthest distributed antenna are too weak to contribute significantly to the received signal. Only the direct rays and the rays with one reflection from the distributed antennas contribute to the received signal as the receiver moves down the tunnel. Fig. 7 shows the rms delay spread for the case of the three transmit antennas radiating different power to the tunnel. Note that there is a steady increase in rms delay spread in the region just before the second distributed antenna. This can be explained by the fact that the second distributed antenna is able to radiate power of sufficient magnitude, which has been delayed by the coaxial cable, toward the first distributed antenna, thus making a significant impact on the rms delay spread. At the region after the second distributed antenna, the rays from the first distributed antenna have already decreased proportionally to the distance traveled, hence explaining for the different rms delay spread values around the second distributed antenna's

Fig. 6. Received signal levels versus distance for the case of the three distributed antennas radiating different power to the tunnel. (a) 900 MHz. (b) 2.0 GHz.

location. Also note that the rms delay spread is dependent on the frequency, which is believed due to the result of the uncompensated coaxial cable transmission loss for this case. The uncompensated coaxial cable transmission loss makes the furthest distributed antenna have the least influence on the propagation. Obviously, it becomes improper to spend the costs for installing this antenna.

It is interesting to compare the rms delay spread values for the above two cases. The rms delay spread values are much higher for the simulcast system with the same radiated power than those with different radiated power. The rms delay spread is critical for broadband simulcast distributed antenna systems. If the rms delay spread is large with respect to the signal pulse width, then equalization techniques should be considered for good reception. Table I summarizes the delay-spread values for the number of distributed antennas up to six. For a given coverage distance it is evident that the rms delay spread decreases for the case of the coaxial cable transmission loss compensated but increases for the case of the coaxial cable transmission loss uncompensated as the number of distributed antennas increases. This indicates

Fig. 7. The rms delay spread versus distance for the case of the three distributed antennas radiating different power to the tunnel. (a) 900 MHz. (b) 2.0 GHz.

that the larger rms delay spread can be avoided by careful design of the distance between the distributed antennas.

V. CONCLUSION

Based on the image theory of ray optics, a theoretical model for simulcast radio propagation channels in rectangular tunnels has been developed. The validated model was applied to study simulcast radio propagation channel characteristics at 900 MHz and 2.0 GHz inside a typical tunnel in order to gain deeper insight and better understanding of this type of channels in tunnels. It was found that simulcast radio propagation channel characteristics depend mainly on the excitation of channels and the separation of distributed antennas.

For simulcast radio propagation channels excited by the distributed antennas with the cable loss compensated, large fluctuations in received signal levels occurred in the capture regions of the distributed antennas for both 900 MHz and 2.0 GHz. The fluctuations in received signal levels in the simulcast regions were larger at 2.0 GHz than at 900 MHz. The rms delay spread

TABLE I
TIME DELAY FOR THE HYPOTHETICAL SIMULCAST DISTRIBUTED ANTENNA SYSTEM

	Equal Radiated Power		Unequal Radiated Power	
	900MHz	2000MHz	900MHz	2000MHz
Delay of a single antenna (ns)				
Min	2.00120	2.00116		
Max	8.95557	8.95453		
Mean	4.31530	4.31499		
Median	3.65486	3.65473		
Std	2.00245	2.00211		
Delay of two distributed antennas (ns)				
Min	6.86185	6.86133	5.74915	3.74977
Max	2123.700	2123.706	198.659	27.1773
Mean	1226.013	1226.021	21.7938	5.20762
Median	1329.989	1330.003	19.5639	4.41027
Std	703.991	703.993	15.7312	19.7710
Delay of three distributed antennas (ns)				
Min	7.81836	7.81790	7.21029	5.90652
Max	1615.809	1615.822	197.852	124.583
Mean	872.132	872.139	90.1984	31.4277
Median	909.666	909.670	69.4904	22.9024
Std	454.341	454.345	49.9782	22.3282
Delay of four distributed antennas (ns)				
Min	8.63550	8.63508	11.4324	7.33935
Max	1425.173	1425.187	246.634	132.268
Mean	735.859	735.865	116.180	52.6497
Median	701.712	701.712	102.994	36.7429
Std	381.564	381.568	60.4162	36.2951
Delay of five distributed antennas (ns)				
Min	9.36810	9.36771	15.8739	9.93945
Max	1320.594	1320.609	266.562	165.672
Mean	660.843	660.848	126.151	63.4357
Median	639.111	639.118	108.149	52.4716
Std	346.098	346.102	60.1998	42.0171
Delay of six distributed antennas (ns)				
Min	10.04233	10.04196	19.8177	12.7846
Max	1249.846	1249.860	268.482	181.655
Mean	611.616	611.621	130.025	69.1970
Median	600.171	600.177	123.362	52.8777
Std	323.483	323.487	57.5791	43.4087

was longer in the simulcast regions than that in the capture regions of the distributed antennas.

For simulcast radio propagation channels excited by the distributed antennas with the cable loss uncompensated, large fluctuations in received signal levels occurred in the capture regions of the distributed antennas near the signal source. The rms delay spread was frequency dependent. It was longer at 900 MHz than at 2.0 GHz. In addition, the rms delay spread was longer for the case of simulcast radio propagation channels excited by the distributed antennas with the cable loss compensated. This larger delay spread was caused by the delay introduced in the transmission medium and can be avoided by a careful design of the separation between the distributed antennas.

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