FM Channel Model Development and its Emulator

Ahmed Hossam Mohammed
Department of Electrical and Computer Engineering
Istanbul Sehir University,
Istanbul, Turkey
ahmedmohammed@std.sehir.edu.tr

Mehmet Kemal Ozdemir
Electrical-Electronics Engineering and Cyber Systems
Istanbul Medipol University,
Istanbul, Turkey
mkozdemir@medipol.edu.tr

***Abstract*—With the widespread availability of Internet, voice only broadcast in the FM Band will soon be abandoned as Internet Radio can provide the same content with no boundaries. The available band can then be exploited for bi-directional wireless services. However, before we can realize this transformation, it is crucial to lay down the channel characteristics of the FM Band to better anticipate its affect on new wireless services. As a starting point, in this study we develop a FM Band channel model for dense Hilly Terrain Regions (HTRs) by the concept of directional channel modelling. The proposed model is verified by exploiting existing channel measurements for the bands near the FM Band and simulations via ray tracing by Wireless Insite tool. Finally, a hardware implementation, capable of emulating the different wireless channel clusters for the FM Band, is introduced. The analysis, simulations, and measurements through the emulator show that the FM Band channel model proposed can indeed represent a typical FM Band channel. Thus, the performance of future wireless systems in the FM Band can be better assessed.**

Keywords*—Directional channel modeling; Multi-path clusters; FM Band, Hardware emulation.

I. Introduction

It is believed that the FM Band is under-utilized with analog radio broadcasting due to widespread usage of Internet streaming of voice media services. Moreover, the inefficient analog transmission of the band necessitates the deployment of more efficient digital systems. For the deployment of such systems, the wireless channel properties need to be determined well ahead for an adequate performance analysis.

For the modelling of the wireless channels, the approach of statistical methods is simple and it has an edge over its alternatives [1]. This approach has been successfully used for many frequency bands, but none of them are for the FM Band since this band is always thought to be for analog voice broadcast. When developing channel models, typically measurement campaigns are carried out. Previous FM Band channel measurements are found to be only for the path loss analysis, and thus they do not reveal critical channel parameters needed for digital communications [2], [3].

As there are no complete measurements for the FM band, we start developing a model by modifying COST-259 model [1], [4] and draw some informed assumptions about key channel parameters. Since the channel models can be different for different environments, as an initial step, we will present the model for Hilly Terrain Regions (HTRs).

Once the channel model is developed, in order to use the developed model in channel emulators, typically software centric emulators are adopted. This approach is flexible as it easily reflects the channel effects on transmitted signals. However, their performance for the real signals has some disadvantages. The software channel emulators typically introduce undesired quantization errors from their up/down-conversion. In addition to this approach, here we propose a hardware wireless channel emulator that reflects the channel effects on the transmitted signal directly in the RF domain. Thus, for the future wireless systems to be deployed in the FM Band, we provide both a software and hardware emulator.

For the rest of paper, we give an overview of the basic concepts in channel modeling in Section II. In Section III, we present channel power delay profile (PDP) and channel impulse response (CIR). Hardware emulation approach is then given in Section IV. The validation of the presented models, discussions, and concluding remarks are given in Section V.

II. Basic Concepts

For the directional channels, circular clusters' visibility regions play an important role [4]. A cluster is considered to be generated by a group of Multi-Path Components (MPCs) that arrive at the receiver within a small time interval [5]. Each MPC has its Direction of Departure (DOD), Direction of Arrival (DOA), and arrival time. The main MPC of a cluster is the first one received. The features of this main MPC characterize the cluster. Interfering Objects (IOs) in a terrain determine a cluster's visibility area. Only a Non Line-of-Sight (NLOS) cluster is associated with an IO that basically determines the features of this cluster. Hence, the determination of the locations of IOs is of a great importance.

For the number of clusters, we assume the existence of at least one cluster (local cluster), an assumption that agrees with the reviewed models [4], [6]. While the first or always existing cluster might be either LOS or NLOS, the existence of any extra cluster is determined by knowing the location of the receiver and specifying if it falls inside the visibility region of this cluster or not. Therefore in our modelling, as a first step, circular visibility regions are assigned to a given region. For any circular region, the number of extra clusters is taken as a Poisson random variable, whose mean decreases with the increase of the planar distance d from the transmitter. This assumption is based on simulations and measurements performed but it contradicts with that of [4], where a constant mean per circle is assumed. The mean of the Poisson random variable at the center of each circle is given by [5]:

$$\lambda = max\left\{(\lambda_i' - (0.2726 * d)) - 1, 0\right\}. \quad (1)$$

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Here λ_i' is the initial average total number of clusters at zero distance from the transmitter and d is the distance in km. The existence of LOS depends on the receiver being in one of the LOS circular visibility regions [4]. Here, a Binomial random variable is used to determine whether the circular region is a LOS region or not, and it is given by [4]

$$p_{LOS}(d) = max\left\{\frac{d_{co} - d}{d_{co}}, 0\right\} \quad (2)$$

where d_{co} represents the distance, above which no LOS is observed. Based on the measurements given for 145 MHz [7], [8], and the COST-259 model, d_{co} can be chosen to be 1 km.

As previously mentioned, no IO is associated with the first cluster, while for the rest, only one IO per cluster is assumed [4]. If more IOs are to be taken into the modelling, only marginal accuracy would be obtained but the implementation would be more complicated. Reported existing delay spread values for HTRs are ≈ 0.1 μsec at a distance of 1 km for 2 GHz band [4], $\approx 5 - 7$ μsec for 900 MHz band [9], ≈ 20 μsec for 210 MHz band [10], and ≈ 25 μsec for 145 MHz band [7], [8]. If we roughly extrapolate the delay spread values for the FM Band, it would be around 40 μsec. For HTRs, the increase in the delay spread with decreasing frequency can be adhered to the propagation characteristics of the channel.

To model the large delay spread of the FM Band, the arrival time of the first cluster is estimated based on the distance from the transmitter. Each following cluster is then assumed to get received after the preceding one by an exponential random variable. A mean of 10 μsec was estimated from the measurements at 145 MHz [7], [8]. To determine the IO locations, distance travelled by the transmitted signal is divided into two different segments: from the transmitter to IO and from IO to the receiver. With this approach, the features of the first cluster are obtained similar to the case in [4] whereas the following clusters' features are modeled similar to the Saleh and Valenzuela model [11].

For the clusters spreads and shadow fading, the standard approach given in [4] is taken. However, we have used different values for the parameters of the FM Band channel. For the log-normal distributed shadow fading, the standard deviation is given by 6 dB for 2 GHz [4] and 6.25 dB for he 145 MHz [8]. Hence, for HTRs it is assumed that the log-normal shadow fading is independent of the frequency band.

Previous studies have found that the median delay spread increases as the distance from the transmitter increases [12]. This can be clearly understood for the outdoor environments at high frequencies of operation, where only one cluster is received for most of the times as shown in Table II in [4]. In this case, the delay spread of the cluster is the same as total delay spread of the channel.

When there are many clusters, the channel delay spread becomes different from the cluster delay spread. For measurements at 145 MHz, after a certain distance from the transmitter, the total channel delay spread decreased with the increase of distance. 5 μsec median cluster delay spread is determined for 1 km separation between the transmitter and the receiver [5].

Lastly, for the clusters gain, different values of the parameters are used in the power gain equations given in [4]. The k_τ factor representing the decay of a cluster power with its delay was suitable to be set to 2 dB/μsec based on 145 MHz measurements [8]. Also the τ_B factor, which indicates the maximum delay after which no more power decay occurs, is set to 15 μsec. Moreover, a correction parameter $s(d)$ is introduced to accommodate the model to the expected FM power levels. Monte Carlo simulations are performed per recommendations from [5], [13]. The received power levels for the FM Band were estimated at each distance d from the transmitter. Iterative Monte Carlo simulations were then performed to obtain $s(d)$ that results in a maximum of 2 dB absolute difference between the expected received power level and the average received power level.

The COST 231-Hata model for the rural and hilly environments can no longer be used to estimate the NLOS path gain, P_{NLOS}, in the power gain equations of [4] as the FM Band is not covered by that model. However, for the FM Band, the actual path loss L in dB is formulated as [3]:

$$L = L_b - (2 * ((log(f_c/28))^2)) + 7.46 \quad (3)$$

where f_c is the frequency of operation and L_b is the loss derived from equation (4.4.3) in [14]. The gain P_{NLOS} is the reciprocal of the linearly-scaled loss.

III. Channel delay Profile and Impulse Response

The number of MPCs within each resolution bin can be of any value as long as their amplitudes are Rayleigh-distributed [4], except for the first bin in the LOS case, which has a Rician-distribution. The resolvable delay bin time is 0.2 μsec for a bandwidth B of 5 MHz [1]. The number of bins within a cluster is determined by dividing its delay spread by the bin-width. Each bin is modelled to contain 15 MPCs that are un-resolvable by the receiver, forming a Multi-Path Group (MPG). Distributing the arrival times of the MPCs uniformly within a given delay bin will then result into the desired distributions. As for the angles of the MPCs, they are also generated uniformly over the interval $[(\theta - \sigma_\theta/2)\ (\theta + \sigma_\theta/2)]$, where θ is the cluster's angle while σ_θ is the angular spread.

The relative PDP for the k^{th} delay bin tap can be given as

$$P_{relative} = P_m \cdot P_k \quad (4)$$

where P_k is the power of the tap that is formed by the summation of the N complex numbers representing unresolvable MPCs and P_m is the gain of the m^{th} cluster to which those MPCs belong. For the generation of the CIR, the amplitude is generated as a Rayleigh random number whose power is represented by the given $P_{relative}$. The phase can be modelled as a uniform random number. These coefficients can also be generated via the method presented in [15].

With the framework presented above, we then simulated the environment for the multipath delays, delay spread, shadowing, directionality, and power levels so that a complete CIR model for the FM Band can be generated for simulations.

IV. Hardware Emulation

Channel emulators are developed to mimic a desired channel model by introducing a given delay profile and Doppler spread. Here we focus on delay profile. A simple way of introducing delays can be through cable extensions [16], but this is impractical for large delay spreads. Instead, a surface acoustic wave (SAW) filter can be used [17], [18]. SAW filters introduce large group delays since acoustic waves travel more slowly than the electromagnetic waves.

In previous studies, two emulation techniques were described: The Cascade Connection Technique and the Feedback Technique [17], [18]. In the cascade technique SAW filters operating at the same center frequency are cascaded to get a larger delay for a given tap. The amplitude and the phase of the tap can be controlled via an attenuator/amplifier and a phase shifter, respectively.

The feedback technique generates taps that are equally spaced in time domain. Similar to the cascade approach, the amplitude and the phase of the first tap is fully controllable. As for the rest of the taps resulting from the feedback, there is no control over their amplitudes and phases since they depend basically on the first entering data sample that goes into the loop over and over. However, the shape of the resulting tap amplitudes can be controlled via gain blocks, where an exponentially decaying power response can be attained. Note that the SAW filter itself also has its own insertion loss. Thus, the resulting PDP is typically an exponential decay even when no attenuators/amplifiers are used. The number of resulting taps from the loop can also be controlled via a variable attenuator.

The cascaded technique is helpful when the predefined channel has relatively low number of channel taps. In such a case, the cascaded technique would be more efficient than the feedback technique due to the presence of full control over the amplitudes and phases of the taps, not to mention the possibility of getting unequally spaced taps. However, in many cases especially when the total channel delay spread is large, the number of desired channel taps to be emulated is large and hence, it might be impractical and very expensive to assign each of those taps to a dedicated branch. Then, the use of feedback technique in emulating the clusters would be more feasible.

The PDP within each cluster generally decays exponentially with time. Therefore, the feedback technique can be used to emulate a single cluster where the first tap of the cluster is fully controlled while the rest of the taps are not. Thus, the proposed emulation method, when there is more than one cluster with large number of taps required per cluster, is a combination of both techniques. Each cluster is assigned to a branch where the maximum excess delay of the cluster can be controlled via a variable attenuator.

Fig. 1 shows the proposed hybrid technique for the emulator. The SAW filters on the left side are for determining the cluster's first tap delay while the SAW filters in the loops are for determining the time delay between each two successive taps within the same cluster.

We have developed multiple prototypes in lab to demonstrate multipath channels. The prototypes used Murata

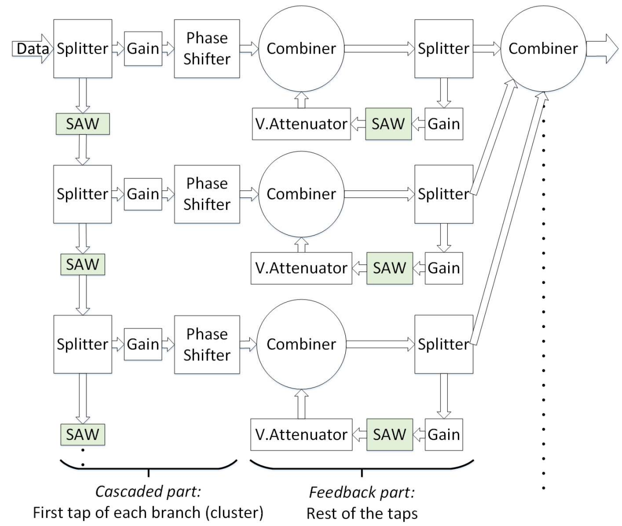

Fig. 1: Hybrid technique emulating multiple clusters by dedicating each of them a separate branch.

PX10023 SAW for the FM Band and Oscilent 813-SL140.0M-77A for 140 MHz band. For visualizing the channel taps, pulse amplitude modulation (PAM) was used. The generated PAM signal consisted of 1 bit followed by a stream of 0 bits. The channel taps of 140 MHz prototype that provide a group delay of about 0.78 μsec can be seen on the scope reading in Fig. 2.

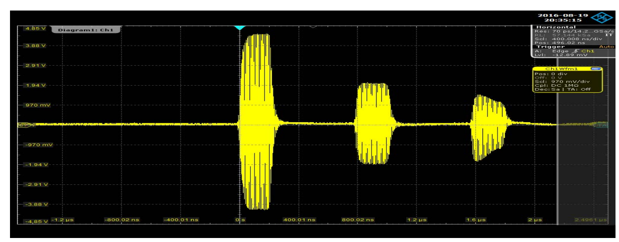

Fig. 2: 3-taps channel emulator via cascading-technique.

For the multiple input multiple output (MIMO) systems, the layout presented in Fig. 1 will be multiplied by the number of channels between transmitter and receiver antenna pairs. Here, the importance of the channel's directional behaviour becomes clear so that a suitable hardware channel emulator is deployed between each transmitting and receiving antenna pair.

V. Validation

For the validation part, we have utilized 145 MHz measurements [8] and preliminary measurements we have performed for 86 MHz and 140 MHz. However, from the preliminary measurement results we conducted, we observe that the channel parameters do not deviate dramatically for the FM Band mostly because the bands are so close to each other. For the given measurements, no clusters were observed for distances beyond 13 km from the transmitter, and therefore total number of clusters was assumed to be zero for these distances. At a closer distance of about 7 km from the transmitter, an average number of clusters of 1.5 was taken. A straight line equation is used for simplicity in (1) and the subtraction of one is introduced due to the existence of the first local cluster regardless of the mean. In the LOS case, clusters with 20 dB power level below the first cluster are ignored. Moreover, it is observed that the delay spread of the channel is indeed very large even for 1 km range NLOS testing as shown in Fig. 3.

RF ray tracing simulations were also performed to validate the idea of total channel delay spread decrease when the distance from the transmitter increases. An isotropic transmitter with 45 dBm output power is assumed. Moreover, a signal with a bandwidth of 5 MHz at the center frequencies of 86 MHz and 140 MHz is generated. The receiver's sensitivity was set to -120 dBm. A receiver set is a set of receiver locations placed at a fixed planar distance from the transmitter. Only the maximum delay spread of each receiver set was taken into account. It was found that at distances beyond 6.5 km, the delay spread decreases with the increase of this distance. However, for distances less than 6.5 km, the simulation results were the opposite. The physical interpretation for this is that with a high chance of LOS occurrence, most of the total power lies in the LOS cluster. This reduces the overall delay spread. In that case, the extra clusters were not received as the delay spread deals with the relative powers unlike the maximum excess delay that takes any signal into consideration as long as its power is above the receiver sensitivity level.

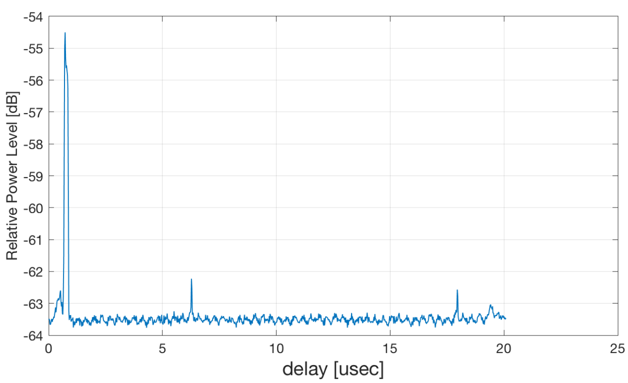

Fig. 3: Channel impulse response for non-line of sight measurement at 140 MHz.

VI. Conclusion

A directional FM channel model has been developed in anticipation that contemporary wireless systems in the near future will be deployed in FM Band. As for the verification of the claims of the proposed model, measurements performed for the bands around the FM Band and computer simulations were exploited. We then developed a SAW filter-based hardware channel emulator to realize the channel taps in the RF domain. This model can be taken as a basis platform for new submodels in the presence of more extended measurements. One of the key observations for the FM Band channels is the increase of the angular spread due to the increase in the number of clusters. Therefore, MIMO antenna technique based systems can be deployed with high performance, resulting in a higher capacity system. Large delay spread on the other hand, requires very long Cyclic Prefix (CP) in orthogonal frequency division multiplexing (OFDM) systems. Having a long symbol duration in turn implies a low data rate. Thus for 5G systems, the design of generalized frequency division multiplexing (GFDM) might outperform OFDM based systems in the FM Band [19].

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