Modeling Survey: The Relationship between Environments, Services, and Network Performance in Wireless Communications Networks

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1. Introduction

1.1 Motivation and Scope

Wireless communications networks have been attracting much attention because of the flexibility and versatility of the services that can be provided. The research and development on wireless communications networks have been active for several decades since the Defense Advanced Research Projects Agency (DARPA) initiated the research on packet radio networks [1]. The design objective of DARPA's packet radio networks was to provide an efficient means of data communications for mobile users in a dynamic ground radio environment. After the successful deployment of DARPA's packet radio networks, many other radio networks have been researched and designed to operate in various types of environments such as satellite [2], conventional macrocellular [3], upcoming microcellular [4], and indoor wireless [5] environments. These networks are similar in that they all apply packet switching technology and are designed to operate in wireless environments. Nevertheless, they are quite different from the viewpoints of the characteristics of radio channels of the environments, the services that are to be supported, and the detailed network architecture such as topology, signaling format, access control, error control, routing control, flow control, etc. For reviews on some of the key issues, see [6].

The design and performance evaluation of wireless communications networks need to consider the characteristics of radio channels in the given environment, the services to be supported, and the network architecture. To develop a model that takes into accounts all the complicated factors mentioned above is next to impossible [7]. Usually, researchers have to concentrate on some aspects of the network and develop performance models (either analytical or simulation) that can capture the key features in these aspects of interest.

This research report is to survey the modeling efforts that have been done in exploring the relationship between environments, services, and network architecture in wireless communications networks. Models that are proposed to explore their relationships will be reviewed and discussed. The focus of our survey is two fold. One is on the characterization of mobile radio channels in various environments, which will directly impact the link quality of a wireless communication link and therefore influence the network performance. The second is on the models that try to relate network performance with the channel models that best describe the environment and the data packet traffic generated by the services to be supported.

1.2 Wireless Environments and Channel Models

One of the challenging aspect of wireless communications networks is the dynamic mobile radio channel in wireless environments. The signals in mobile radio channels are subject to propagation path loss and multipath fading. Propagation path loss refers to the phenomenon that the mean strength of radio signals decrease as the distance between transmitters and receivers increase due to the free space loss and the groundwave loss. The mean received signal strength will vary if transmitters, receivers or both are mobile. Multipath fading is the phenomenon that the strength of the received signal has a fast fluctuation. Multipath fading occurs because the received signal is the superposition of a large number of reflected waves due to the surrounding buildings and roads. The strength of the sum of the signals from multipaths has fast variations because of the random path delays.

Though all subject to propagation path loss and multipath fading, the channels in different wireless environments could have very different statistical characteristics. The characteristics of the channel in a wireless environment have a strong impact on the design of error control protocols. For instance, the choice of forward error correction (FEC) codes and automatic repeat request (ARQ) protocols depends on the statistics of the errors due to channel impairment [8]. If the packet error probability is low, simple ARQ protocol might be a good choice. Whereas if the packet error probability is high, more complicated FEC coding might be necessary in order to turn a noisy channel into one with certain level of quality. The channel characteristics will also influence the selection of other physical layer parameters such as signalling formats (narrowband or spread spectrum) and modulation schemes.

Three typical wireless environments will be considered here, namely macrocells, microcells and indoor picocells. The characteristics of channels, in terms of parameters of channel models, obtained by measurements will be reviewed in Section 2.

1.3 Network Architecture and Performance

Among the 7 layers of the OSI reference model of network architecture [9], we will focus on the physical layer and medium access control layer. For the physical layer, we will consider both of the signalling formats, i.e., narrowband and spread spectrum, and their impact on the modeling of wireless networks. The characteristics of channels are expected to come in and interact with the physical layer model. The effect of modulation and forward error correction coding will also be part of our interest. In terms of modeling of wireless networks, different signalling formats will lead to the most different representations of the network compared to other physical layer parameters. Section 3.1 will review this aspect.

For the medium access control layer, we will look into the models that consider the interplay of channel access protocol, network topology, data traffic, the physical layer, and wireless channels. The attention is to survey how these factors are modeled and affect network performance. Fig. 1 illustrates the relationship between environments, services, network architecture and performance.

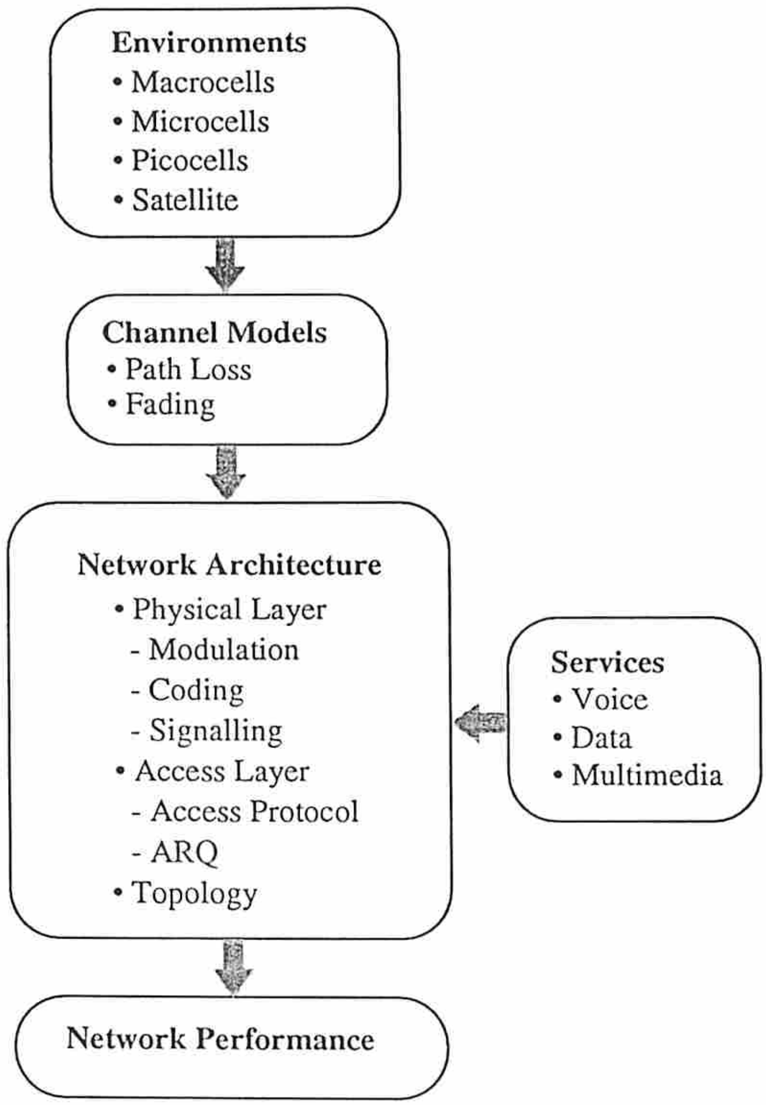

Fig. 1. The relationship between environments, services, network architecture, and performance.

2. Wireless Communication Channels and Environments

2.1 The Basics

The most fundamental task in modeling a mobile radio network is to model a radio link without multiuser interference, called channel modeling. The common features of the radio channels in different wireless environments will be described here. The specific values of the parameters of channel models from measurement results in the 3 environments considered will be detailed later on.

2.1.1 Path Loss

The electromagnetic waves propagating in a mobile radio channel suffer large-scale path loss and multipath fading. Large-scale path loss refers to the phenomenon that the mean received signal power decreases as the distance between transmitters and receivers increases. This is due to the wavefront spreading in the free space and the attenuation caused by the ground surface. Path loss will to some extent limit the maximum communication range or determine the reuse distance in a cellular system where the radio spectrum is reused over spatially separated areas.

2.1.2 Multipath Fading

Multipath fading refers to the phenomenon that the instantaneous signal strength varies rapidly over a small scale area. With reflections, scattering and diffraction from terrain features (such as walls, building, mountains, etc.) and vehicles, radio waves (signals) arrive at a receiver via several paths from various directions have different time delays and phase delays. So the received signal, which is the vector sum of the multipath signals has substantial variation in the signal amplitude. Moreover, the spread in the arrival times of different paths have a strong impact on the reception of the signals being transmitted. Multipath fading is a spatial phenomenon in nature, but the relative mobility between transmitters and receivers manifest it as a time-variant phenomenon. The characterization of fading mobile radio channels can be divided into 2 categories, i.e., narrowband and wideband characterization.

Narrowband Characterization

Narrowband characterization is sufficient for transmissions where the symbol duration (inverse of the signal bandwidth) is much greater than the spread in propagation path delays (called delay spread). For narrowband transmissions, the multipath results in rapid fading of the received signal envelope. So it is very important to know the distribution of the instantaneous envelope of the received signal in order to determine the link quality. In addition, how the envelope of the received signal changes in time is also an important statistics. This is related to the Doppler spread that is caused by the relative mobility between transmitters and receivers [10].

Narrowband characterization is not appropriate when the symbol duration is not much greater than the delay spread. In this case, different frequency components in the received signal have different phase lags due to the differential path length in different paths, and hence tend to fade independently. This is called frequency-selective fading and will cause intersymbol interference (ISI), which results in an irreducible error rate of the received signal. Wideband characterization of mobile radio channels is needed to study techniques, such as adaptive equalizer, advanced modulation schemes and spread spectrum signalling, to combat with multipath fading.

Wideband Characterization

Many researches have been done on the wideband measurements and modeling of multipath fading channels. The wideband measurements endeavor to find the impulse response of the channel. Many statistical models for the channel impulse response have been reported in the literature. Basically, they can be classified into 2 categories: (1) continuous representation, e.g., Gaussian wide-sense stationary uncorrelated scattering channel, and (2) discrete representation, e.g., ray models. The continuous representation will be discussed later on.

The channel impulse response in ray models is the sum of a (possibly random) number of resolvable paths which have random path amplitudes, path phases and path arrival times as the parameters of the channel. Ray models are the most popular technique to characterize the wideband characteristics of a multipath fading channel. In ray models, the low pass equivalence of the channel impulse response is the sum of a number of delayed impulses with different amplitudes, phases, and delays due to the multipath effect. By giving different statistics to the parameters of the impulse response of the ray model, we can model different multipath channels. Of course, the statistics of the parameters have to be validated by measurement results.

Because of the random and time-variant nature of mobile radio channels, their characteristics can only be described statistically. Many statistical models have been proposed. Measurement of the parameters in these statistical channel models in various environments have been an active research area for 2 decades. Some of the key results will be introduced in the following.

2.2 Channel Models for Macrocells

One continuous representation for macrocellular channel is Gaussian wide-sense stationary uncorrelated scattering (GWSSUS) model [11], [12], [13], [14]. The model can well characterize the mobile radio channel in macrocellular environments where the signal amplitudes have Rayleigh distributions. This model also fits other channels such as ionospheric skywave HF channel pretty well [15]. The basic reason is that there usually exists no LOS between transmitters and receivers and hence the received signal is the sum of a large number of uncorrelated scattering and reflected rays. By the law of large number, the signal strengths of the in-phase and quadrature components have a Gaussian distribution. A GWSSUS channel is characterized by the power delay profile, which has 2 key parameters: mean excess delay and delay spread. Mean excess delay and delay spread are the first and second central moment of the power delay profile. These 2 parameters have strong correlation with the performance of a communication link.

For macrocellular environments, several discrete models are developed in the literature [16], [17]. The path arrival times were modeled as a Poisson sequence by [16], and as a modified Poisson process by [17]. The modified Poisson process matches measurement results better because the multipath rays usually arrive in clusters. Many statistical distributions are considered for the amplitudes of the multipaths, e.g., Rayleigh, Rician, Nakagami, lognormal, and the combinations of lognormal and others. Hashemi [18] developed a simulation model that incorporated the work in [16], [17].

2.3 Channel Models for Microcells

Harley [19] measured the short distance attenuation at 900MHz and 1.8GHz using low antenna heights (5m-20m for fixed site and 1.5m for mobile vehicle). He found that the path loss in short distance (less than 1 km) show two distinct regions separated by a breakpoint. The measurements show that extrapolation of the Okumura [20] and Hata [21] formulae into low antenna height, short distance area is not valid. More specifically, the slope of the power attenuation curve is much less than extrapolating the results of [20] and [21]. The key parameters of the proposed model for path loss in microcells are (1) the basic attenuation rate for short distances, (2) the additional attenuation rate for distances greater than the breatpoint, and (3) the breakpoint.

Rustako et al. [22] conducted a propagation experiment to characterize microcell channels with various antennas at 2 distinct frequencies (900MHz and 11GHz) in different environments, from rural to dense urban. They found that the propagation in rural areas can be well modeled by the interference of the direct LOS ray and a specular road-reflected ray. In urban areas, the additional 4 rays to account for the specular wall-reflected rays can adequately represent microcell propagation. In suburban areas, the 2-ray model can approximately predict the power attenuation but the addition of 2 or 4 wall-reflected rays can represent the propagation in more details. The multiray models can predict the received signal power and the structure-induced delay spread as functions of vehicle position in microcells. Directional horn antenna mounted on vehicles is shown to be able to suppress the wall and road reflections and hence reduce the delay spread. This can facilitate communications at higher signalling rate. The issue of delay spread will be discussed in more detail later on. Xia et al. [23] measured the microcell propagation using 3 transmitting antenna heights (3.2m, 8.7m and 13.4m) and 2 frequencies in 900MHz and 1.9GHz bands. Measurements from 5 test sites in rural, suburban and urban areas are collected. For all LOS measurements, even in different environments, the power attenuation with distance shows 2 distinct regions separated by a breakpoint. In addition, it is found that the location of the breakpoint for different frequencies and antenna heights can be well predicted based on the first Fresnel zone clearance. For high frequencies, the first Fresnel clearance is approximately proportional to the antenna heights and the frequency. By regression analysis, the attenuation slope is found to be less than 2 (ranging from 1.0 to 1.8) before the breakpoint and greater than 2 (ranging from 3.6 to 13) after the breakpoint. This suggest that the break distance can be used to define the cell size of microcells. Ray models are used to predict the propagation in different environments. The 2-ray model can give the spatial average of signal variations predicted by the 4-ray model, but does not predict the rapid variations of the received signal due to the interference of multipath. The 4-ray model can predict the fluctuating received power even after the first Fresnel breakpoint, where the 2-ray model gives a smooth decay. More detailed models (e.g., 6-ray model [22]) that consider double reflected rays give only a slight refinement over the 4-ray model. Due to the smaller reflection coefficient of vertical polarization compared to that of horizontal polarization, vertical polarized antennas show less severe two-path fading.

Blackard et al. [24] measured the (wideband) path loss and delay spread as functions of antenna heights for two microcellular environments in the 1900Hz band. By regression analysis, it is found that the first Fresnel clearance distance is as accurate as the minimum mean squared error breakpoint (which was calculated iteratively.) Measured delay spreads were found to be functions of antenna heights. More specifically, as the antenna height increases, the mean and standard deviation of delay spreads increase.

Parson et al. [25] measured LOS propagation for microcellular urban streets at 1800MHz with 3 antenna heights (7m, 14m and 21m). Experimental results for both narrowband and wideband are obtained. A new probabilistic 10-ray propagation model was proposed. The narrowband result shows that (1) the fast fading signal amplitude closely fitted a Rice distribution, (2) antenna heights have effect on the coverage area, and (3) the profile of signal strength with distance obtained by the 10-ray model has a very close resemblance to the measured data. The 10-ray model is further enhanced by introducing a probabilistic factor for each reflected ray to account for the absence of reflected rays due to the imperfect surface and the discontinuity of walls. The signal strength profile has almost complete resemblance with the measured results. The probabilistic factor should be chosen according to the environment. For heavily dense urban areas, it should be set almost to one. For less dense urban areas, it should be set between 0.98-0.96, but perhaps with less number of rays.

The theoretical delay spread for 2, 4, 6, 8 and 10 rays models are calculated. As expected, the delay spread increases with the number of rays. Also the antenna height was found to have negligible effect on the theoretical delay spread. However the theoretical delay spreads did not compare well with the measured results. This discrepancy was attributed to the nature of the buildings in the test site.

2.4 Channel Models for Indoor Picocells

Recently Yegani [26] measured the channel impulse response of factory radio channels. The statistics for the number of paths, the path arrival times, and the amplitudes of paths are measured. Different statistics compared to the macrocellular channel are obtained. For example, Yegani found that the number of paths has a modified beta distribution and the interarrival times have Weibull distribution. Rapapport [27] developed a simulation model for factory radio channel. In addition to the number of paths, the likelihood of path arrival, the amplitude distribution, this model also models the correlation of path amplitudes.

3. Network Architecture and Performance Models

3.1 Architecture

Among the many aspects of modeling a wireless network, the most complicated part is perhaps the modeling of the transmission and reception of packets in the wireless environment. If this part can be well taken care of, the other facets of the network are probably can be very faithfully modeled by network of queues, for which many analytical and simulation tools exist [28], [29]. The complexity of modeling the transmission and reception is wireless comes from 1) the dynamic mobile radio channel, 2) the multiuser interference, which are driven by the services (possibly multimedia) to be supported by the network, and 3) the strong dependency on the physical layer parameters such as signalling formats, modulation, and FEC coding. The following will explain how different signalling formats can change the network models dramatically.

3.1.1 Narrowband

With narrowband signalling in a nonfading channel, a packet for transmission is directly modulated on to a carrier is then radiated by an antenna. A transmission will be successfully received if no strong noise is present during the reception of the packet. Simultaneous transmissions within a certain range called the interfering range (which depends on the path loss,) will result in errors for both transmissions. The phenomenon is called collision. If the simultaneous transmissions are far apart enough, the strength of the signals will differ substantially so that the stronger one can be successfully received and the weaker one will be rejected as noise, a phenomenon called the capture effect. To avoid collision, users within a certain range that will potentially interfering with each other, should coordinate their channel access so that different packets can be separated in the time domain.

Due to the strong interfering nature between the users within the interfering range, the existence of the communication link between a particular transmitter and receiver pair is highly dependent on the activities of other users in the interfering range dynamically.

3.1.2 Spread Spectrum

Spread sepctrum signalling [30] employs some kind of coding technique to protect packets from other noise and interference. In particular, a packet for transmission is first spread by a pseudo-noise spreading code before being modulated. At the receiver, the despreading operation help to increase the strength of the desired signal against the background noise and interference. With the spreading protection, simultaneous transmission will effectively appear as some increase of noise power to the receiver instead of fatal collision effect. As long as the number of simultaneous transmissions is not too large (compared to the spreading factor), a packet can be successfully received.

As applied to a multiuser communication network, users can transmit at the same time and their packets can be separated in the code domain. Therefore the effect of simultaneous transmission is not fatal as in the case of narrowband. But due to the prolonged packet transmission time with spreading, many packet transmissions will overlap in time and make the communication link between a particular transmitter and receiver pair experience a persistent interference but less dynamic compared to the narrowband case.

3.2 Network Performance Evaluation

With the propagation models surveyed in Section 2, the next task is to develop performance models for the wireless network with the given channel access protocol and the physical layer modem structure. In general, there are 3 approaches for performance evaluation of communications networks [31].

(1) Analytical approach. This approach is to extract the key parameters and then create analytical (mathematical) models to study the performance of the radio network being considered. To be able to represent a complicated radio network mathematically, some simplified assumptions have to be introduced. Though the performance estimate might not be very accurate, this approach can give designers a first impression on the network and help to find out the potential problem at the early stage of design.

(2) Simulation approach. This approach is to create a more realistic network model and evaluate its performance by computer simulation. Simulation can be used to study the network behaviors in more details with the powerful computational capability of modern computers. Nevertheless, the computer run time may become prohibitively long as the simulation model get more and more complicated.

(3)Hybrid approach. By combining the merits of the first two approaches, this approach incorporates some analytical models (for parts of the network where good analytical models exist) into the simulation model to speed up the simulation time. This approach can give a reasonably accurate performance estimates in much less time than the pure simulation approach.

The following sections examine how the 3 approaches above are used to evaluate performance of wireless networks. In particular, we look at the impact of channel models and services on network performance.

3.3 The Impact of Channel Models on Network Performance

The two major characteristics of mobile radio channels are path loss and multipath fading. Their effects on network performance will be discussed as follows. Depending on the definition of network performance, the severity of the impact of different channel models may be different.

The impact of path loss on the capacity of cellular have been investigated in [32], [33]. Basically, the path loss exponent (typically ranging from 2 to 4) will determine the reuse distance of cellular system, which directly determine the capacity. For a cellular system without frequency reuse [34], the path loss exponent will determine how much interference is from users in other cells. The stronger the other-cell interference, the less the system capacity is.

The effect of path loss exponent on the reliability performance of a local packet radio network with hard real-time communication requirement is considered in [35]. In essence, the path loss will determine the reuse distance, thus the number of users that will potentially interfere with each other, and finally the reliability of the network, which is defined to be the probability that real-time packets cannot be successfully delivered within a specified time interval.

The fading statistics of mobile channels have a great impact on the quality (the performance of interest) of a call in a cellular phone system. The performance measure of cellular voice communications is usually the outage probability which specifies the probability that the bit error rate will be above the threshold that is required for some minimum link quality. To compute the outage probability, the usual assumption is that there is some fixed number of co-channel users which will interfere the link being considered. Without considering the dynamic fluctuation of the number of co-channel users, the details of the effect of modulation, coding and spreading can be put into the performance models, e.g., [36], [37], [38], [39].

The effects of fading on the performance of a mobile data network with [40]. Network throughput (the performance of interest) is found to be sensitive to the fading statistics when the data traffic load is high. However, if the data traffic is low, the performance is not sensitive to the fading statistics.

Throughout the discussion above, the network is designed to support one type of services, either voice or data services but not both. This restriction simplify a lot on the performance evaluation of wireless networks. If a wireless network is designed to support multiple services (with possibly different service requirements), the network model will be much more complex and is the focus of the next section.

3.4 The Impact of Multimedia Services on Network Performance

Wireless networks that can provide multimedia services, such as voices, images, and data, are attracting lots of attention because people want to extend the services that are provided by wired-based networks to wireless environments [41]. The design of network control protocols such as access control and error control should be based on the characteristics of data traffic sources and service requirements. Different traffic sources could need very different service requirements. Packets generated by voice sources need the packet delay to be bounded but can tolerate some errors or losses. Whereas data packets can be delayed to some extent but cannot tolerate losses. Therefore, the packets coming from different sources need to be treated differently in order to make the sharing of the common radio channel efficiently.

Analytical network performance models for this type of integrated services systems usually neglect the complexity of channel models and focus on the dynamic collision (for narrowband signaling) or interference (for spread spectrum signaling) generated by the multimedia sources. An example is [42] where the performance of PRMA (a narrowband access protocol) for integrated voice/data network is evaluated. There are performance models for wireless integrated voice/ data CDMA networks, which focus on the network performance under the aggregate interference power generated by multimedia sources [43], [44]. The accuracy of the approach of using simplified channel models to analyze the performance of multimedia networks needs to be validated by more realistic models or prototype systems, which is the considered as follows.

3.5 The Joint Effect of Channels and Services on Network Performance

Most of the models considered in Section 3.3 and 3.4 emphasize either the dynamic channel due to fading or the dynamic interference due to multiple services but not both. To faithfully account for the joint effect of channels and data traffic generated by the services supported, more elaborate network models are necessary. In the following, we consider a narrowband channel access protocol for data communications. We will show that the model complexity grows as the network performance measure of interest changes.

In narrowband mobile slotted ALOHA networks [45], the performance measure of interest is usually the network throughput and the average delay. To determine network throughput, most analytical models assume that the packet arrival process is Poisson with the offered load given by some spatial distribution, e.g., [46], [47], [48]. Then the network throughput is expressed as a function of the conditional capture probabilities, which is the probability that the common receiver will successfully receive a packet given some number of simultaneous transmissions. All the details of the physical layer parameters are considered in computing the conditional capture probability, including the spatial distribution of users. To find the average delay, the most popular user data traffic model is the single-buffered terminal model, in which a user is alternating between the idle state and the backlogged state [49], [50], [51]. The network behavior then can be modeled as a discrete-time Markov chain with the state being the number of backlogged users. The equilibrium state probabilities then can be solved and the average delay can be obtained by the Little's result. So we have seen that the performance model for mobile slotted ALOHA networks becomes more complex as the performance measure of interest changes from the network throughput to the average delay.

If the performance measure of interest is the user average delay as a function of the distance relative to the base station, more detailed data traffic model is required, e.g., [52]. Furthermore, if the performance measure of interest is the user packet delay distribution as a function of the distance relative to the base station, only simulation model can obtain that kind of detailed performance. It can be seen that as the performance measure of the network designers/analysts get more and more detailed, the reliance on the simulation model becomes more and more significant.

In order to get the performance estimates in reasonable time, the physical layer parameters cannot be too complex. So there is a trade-off between the accuracy of the performance estimates and the simulation run time. It is desirable to have a modeling environment that allow network designers to choose the level of detail in the performance models depending on their needs.

The flexibility of the modeling environment comes from the uniform interface between different component models. With the interface unchanged, different representations of a particular component model at various levels of detail can be experimented, and the results can be compared against each other.

4. Conclusion

Many activities on modeling, measurement, and simulation of mobile radio channels have been reported in the literature. We have identified some of the key developments that are relevant to wireless networks modeling in some typical environments. We have seen the trend that people are trying to understand the propagation characteristics of mobile radio channels in more details. The interests of channel measurement range from simple statistics such as the path loss law, the delay power profile, to more detailed statistics such as the number of paths, the distribution of path amplitudes, and the correlation between multipaths. With more detailed knowledge about the channel, people can design and accurately evaluate more advanced counter measures against the notorious multipath fading effect in mobile radio channels.

To evaluate the performance of radio communication systems is not an easy task. The performance of the radio communication links depends on the radio access technology which include the radio channel access schemes and the combination of modulation/coding/spreading techniques. To evaluate the link performance accurately, we need to be able to model the joint interference due to thermal noise and multiuser interference. But the joint interference in a radio link depends on the data traffic which is generated by mobile users with possibly multimedia services requirement. So we can see that there exists a lot of factors which can potentially impact the communication network performance. Among these factors, some of them will be more important than others as far as the accuracy of performance estimates are concerned. To get sufficiently accurate results yet with reasonable computational cost, we should model the important factors in details and use approximations for the other factors. However, for different performance measures of interest, the important factors may be different. So it is the final goal of this research to develop a radio network modeling environment that allows network designers/analysts to model the radio network at different levels of detail.

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