申请上海交通大学硕士学位论文

移动网络通信质量测试、建模与系统实现

论文作者 马 永森

学　　号 1100329074

指导教师 龙 承念　教授

专　　业 控制科学与工程

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Performance Measurement and Modeling in Mobile Wireless Networks

Yongsen MA

Supervisor

Prof. Chengnian Long

Depart of Automation

School of Electronic, Information and Electrical Engineering

Shanghai Jiao Tong University

Shanghai, P.R.China

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移动网络通信质量测试、建模与系统实现

摘　　要

安全始终是高速铁路发展过程中的首要目标，而 GSM-R 网络则是保证高铁系统安全性的重要环节，因此有必要对 GSM-R 网络进行在线实时测试，在确保 GSM-R 网络正常通信的基础之上，保证整个高铁系统的稳定运行。但是由于高铁系统具有较为特殊的无线传播环境，传统的信号强度测试算法无法直接应用于 GSM-R 网络测试中，例如高铁线路周围地形复杂多变以及列车处于高速运行状态，这就要求 GSM-R 网络信号强度测试算法必须具有实时高效的特点，以适应高速铁路的特殊要求。

关键词： 上海交大　饮水思源　爱国荣校

Performance Measurement and Modeling in Mobile Wireless Networks

ABSTRACT

Recent studies show that Received Signal Strength (RSS) is a weak indicator for 802.11n channel quality due to the large transition window with respect to Packet Delivery Ratio (PDR), and there exists a fundamental and inevitable tradeoff between the accuracy and overhead in channel measurement and prediction. This is further complicated by the distinctive features in mobile 802.11n networks, specifically, multiple PHY/MAC settings and spatial-temporal variation channels. In this work, we present an online PDR-RSS modeling framework for mobile 802.11n networks. The proposed online PDR-RSS model incorporates a novel design by exploiting both packet-level and physical-level metrics, along with the diversity property of multi-configuration simultaneously to overcome channel capturing problem in the existing PDR-RSS models. This online framwork also strikes a balance between the measurement overhead and accuracy. We further develop a rate adaption algorithm, Graded Rate or GradedR, to advocate the advantage of online PDR-RSS modeling framework. GradedR adopts an online rate selection process with high precision. Through a real world implementation on our testbed, we evaluate the GradedR over different scenarios and routes. The experimental results indicate that GradedR can achieve throughput gains up to 40% over the Minstrel rate control algorithm under different MIMO configurations.

The on-line and dynamic estimation algorithm for Rician fading channels in GSM-R networks is proposed, which is an expansion of local mean power estimation of Rayleigh fading channels. The proper length of statistical interval and required number of averaging samples are determined which are adaptive to different propagation environments. It takes advantage of the sampling signals and Rician fading parameters of last estimation to reduce measurement overhead. The performance of this method was evaluated by measurement experiment along the Beijing-Shanghai high-speed railway. When it is NLOS propagation, the required sampling intervals can be increased from 1.1λ in Lee's method to 3.7λ of the on-line and dynamic algorithm. The sampling interval can be set up to 12λ although the length of statistical interval decreases when there is LOS signal, which can reduce the measurement overhead significantly. The algorithm can be applied in coverage assessment with lower measurement overhead, and in dynamic and adaptive allocation of wireless resource.

KEY WORDS: GSM-R, 802.11n, local mean power estimation, packet delivery modeling

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主要符号对照表

GSM	Global System for Mobile communications	全球移动通信系统
GSM-R	GSM for Railways	铁路移动通信系统
WLAN	Wireless Local Area Networks	无线局域网络
Wi-Fi	Wireless Fidelity	无线保真
MIMO	Multiple-Input Multiple-Output	多天线系统
OFDM	Orthogonal Frequency Division Multiplexing	正交频分复用
RSS	Received Signal Strength	接收信号强度
SNR	Signal to Noise Ratio	信噪比
SINR	Signal to Interference plus Noise Ratio	信号与干扰加噪声比
CSI	Channel State Information	信道状态信息
PDR	Packet Delivery Ratio	数据包传输成功率
QoS	Quality of Service	服务质量
GPS	Global Positioning System	全球定位系统
GIS	Geographic Information System	地理信息系统
BS	Base Station	基站
MS	Mobile Station	移动台
AP	Access Point	接入点
EWMA	Exponentially Weighted Moving Average	指数加权移动平均
DWSA	Dynamic Weighted Sliding Average	动态加权滑动平均
MCS	Modulation and Coding Scheme	调制与编码策略
MAC	Medium Access Control	媒介访问控制
SDM	Spatial Division Multiplexing	空分复用
MSDU	MAC Service Data Units	服务数据单元
MPDU	MAC Protocol Data Units	协议数据单元
A-MSDU	Aggregation of MSDU	聚合服务数据单元

A-MPDU	Aggregation of MSDU	聚合协议数据单元
STBC	Space Time Block Coding	空时编码
GI	Guard Interval	保护时隙
LGI	Long Guard Interval	长保护时隙
SGI	Short Guard Interval	短保护时隙
ACK	Acknowledgement	应答
MLE	Maximum Likelihood Estimation	最大似然估计
MMSE	Minimum Mean Square Error	最小均方误差
XML	eXtensible Markup Language	可扩展标记语言

第一章 信道状态采样与估计

安全始终是高速铁路发展过程中的首要目标，而 GSM-R 网络则是保证高铁系统安全性的重要环节，因此有必要对 GSM-R 网络进行在线实时测试，在确保 GSM-R 网络正常通信的基础之上，保证整个高铁系统的稳定运行。但是由于高铁系统具有较为特殊的无线传播环境，传统的信号强度测试算法无法直接应用于 GSM-R 网络测试中，例如高铁线路周围地形复杂多变以及列车处于高速运行状态，这就要求 GSM-R 网络信号强度测试算法必须具有实时高效的特点，以适应高速铁路的特殊要求。

1.1 问题描述

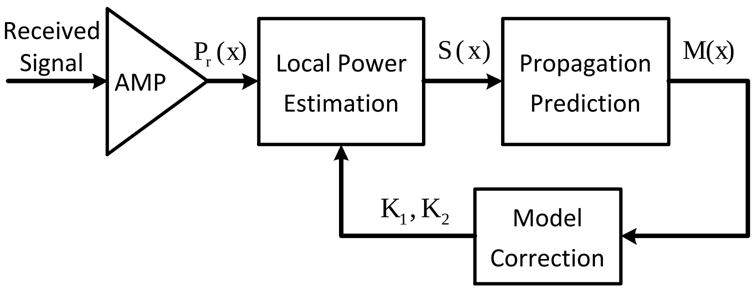


图 1–1 接收信号强度测试过程

Fig 1–1 Basic Procedures of Radio Propagation Measurement

无线网络接收信号强度测试过程如图 1–1 所示，测试系统通过包络检测得到接收信号强度，然后通过信号动态采样算法，得到当前阴影衰落与多径衰落信息，一方面用来对网络通信状态进行评估，另一方面作为网络越区切换的判断依据。同时根据采样数据进行无线传播预测，对网络的覆盖情况进行评估，最后对估计算法与预测模型进行参数修正。

1.1.1 现有工作

移动无线网络信号强度测试的一个基本问题是本地均值的可靠估计，即如何确定合适的采样参数以准确地获取当前信号强度，同时在测试精度与开销之

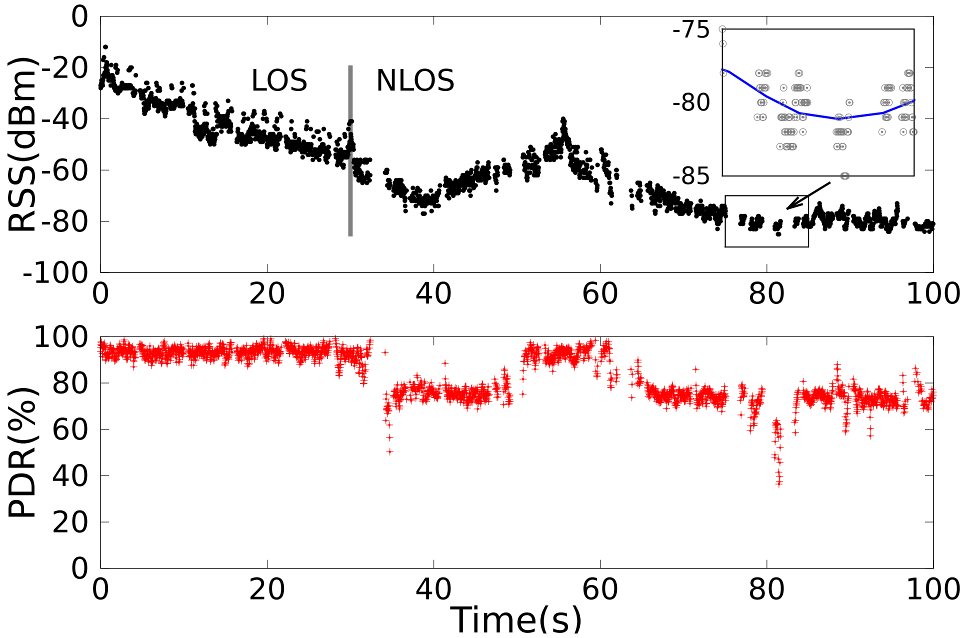


图 1–2 移动无线网络时变特性

Fig 1–2 Time varying of RSS in mobile wireless networks

间实现合理平衡。移动无线网络接收信号强度通过特定统计区间内一定数量的采样点数的算术平均获得，因此采样频率决定了信号强度的测试精度与开销，因此需要根据无线传播环境的变化对信号的采样频率进行实时调整，对于 GSM-R 网络而言合理有效的采样精度与开销的平衡尤为重要。

如图 1–2 所示，移动无线网络接收信号强度具有明显的时变特性，其中包括大尺度衰落和小尺度衰落，如果信号采样的统计区间过长或采样频率过低，系统将无法对小尺度衰落作出合理评估，从而难以保证可靠的数据传输；相反，如果统计区间过段或采样频率过高，大尺度衰落和小尺度衰落难以有效区分，从而导致网络状态的不稳定，例如接收信号强度在切换门限附近波动造成的乒乓切换效应。

William C. Y. Lee 在 1985 年最先提出移动网络信号强度采样算法，即 Lee 氏采样算法 [1]，该算法以移动网络无线传播传播模型为基础，在无线传播环境服从瑞利衰落的假设条件下，推导出信号强度的本地均值测量中的统计区间长度与采样点数。Mark D. Austin 在其蜂窝网络的切换算法中对莱斯衰落条件下的采样算法进行了推导 [11]，得到统计区间与采样点数的近似解，但是该算

法过程复杂且计算量较大。David de la Vega 在 2009 年提出通用 Lee 氏采样算法 [2]，在不需要知道多径衰落具体分布的条件下，利用实测采样信号进行估计，得到实际网络环境所需要的统计区间与采样点数。由于高速铁路无线环境的复杂性及其对安全性的特殊要求，以上的本地均值估计算法难以在较低的测试开销条件下实现可靠的测试精度，不符合高铁环境实时测试的要求，因此无法直接应用于 GSM-R 网络中。

1.1.2 存在问题

- **高速移动特性** GSM-R 网络处于高速运行状态，相同情况下需要对接收信号强度进行更为频繁的采样，同时不能够影响到网络的正常通信。

- **无线传播环境** GSM-R 网络一般存在直射路径，因此应当采用莱斯信道对 GSM-R 网络的无线传播环境进行刻画，由于莱斯信道衰落参数及其估计算法的复杂性，The basic consideration in local power estimation is the sampling frequency which is determined by the length of statistical intervals and number of averaging samples. The received signal strength of wireless propagation is influenced by the environments, so the local mean power estimation should be dynamic to the networks status, especially for GSM-R networks. Fig. **??** demonstrates the time varying and location difference characteristics of received signal strength $P_r(x)$ in mobile networks, which indicates the facts that Fig. 1–2: certain received signal strength carve contains both long-term and short-term fluctuation; Fig. 1–3: the overall received signal strength shows different characteristics for different routes. Since the received signal strength $P_r(x)$ is changing in both large and small time scale, the local mean power estimation should also be adaptive to this fluctuation.

1.2 无线传播模型

由于高速铁路沿线地形复杂多变，一条线路通常会经过山地、平原、隧道和高架等地形，如图 1–4 所示，从而造成 GSM-R 网络无线传播环境的复杂性。同时图 1–4 中可以看出，高速铁路无线传播环境大多较为平坦，同时为了尽量保证 GSM-R 网络的可靠性，基站位置通常距离高铁线路很近，而且小区半径

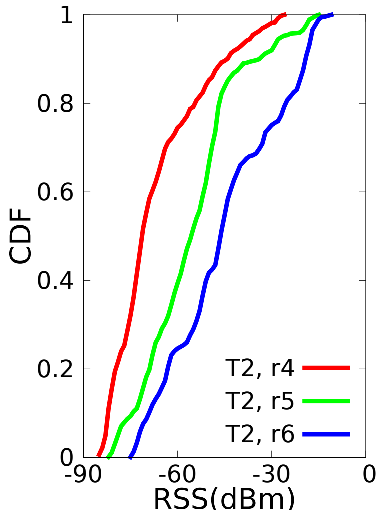


图 1–3 移动无线网络位置差异性

Fig 1–3 Location differences of RSS in mobile wireless networks

一般设置为 3-6km，从而造成移动终端与基站之间一般存在直射路径（Line of Sight, LOS），因此 GSM-R 网络的无线传播应该刻画为莱斯衰落。

在 GSM-R 网络空中接口的无线通信中，接收信号强度可以视为阴影衰落与多径衰落的叠加，如式（1–1）所示，

$$p_r^2(x) = s(x)h(x) \tag{1–1}$$

其中 $s(x)$ 为阴影衰落，服从高斯过程；$h(x)$ 为多径衰落，服从复高斯过程；x 可以视为移动台与基站之间距离，利用列车运行速度公式可以转化为时间变量。如图 1–5 所示，GSM-R 网络中移动台与基站间距离 d 在 10m 左右，因此 $\Delta x = \sqrt{d^2 + v_{train}^2 \cdot \Delta t^2}$ 可以简化为 $\Delta x = v_{train} \cdot \Delta t$。同时式（1–1）可以表示为对数域形式，如式（1–2）所示，

$$P_r(x) = S(x) + H(x) \tag{1–2}$$

其中 $P_r(x)$、$S(x)$、$H(x)$ 分别为接收功率与信号衰落在对数域的表示，即 $P_r(x) := 10\log(p_r^2(x))$，$S(x) := 10\log(s(x))$，$H(x) := 10\log(h(x))$。

(a) 高架

(b) 隧道

(c) 山区

(d) 平原

图 1–4 GSM-R 网络无线传播环境

Fig 1–4 Radio Propagation Environments and terrains of GSM-R Networks

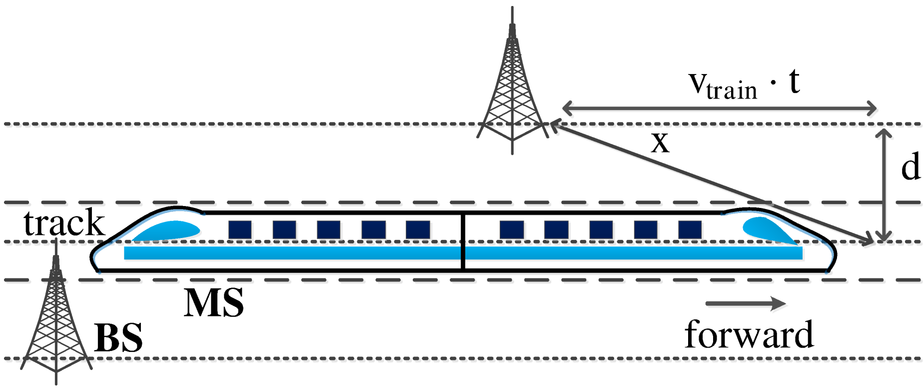


图 1–5 GSM-R 网络移动台与基站间距离

Fig 1–5 The distance between MS and BS in GSM-R networks

1.2.1 阴影衰落

阴影衰落可用如式（1–3）所示的高斯过程表示

$$s(x) \sim N\left(m(x), \sigma_s^2\right) \tag{1–3}$$

其中均值 $m(x)$ 主要受路径损耗影响，方差 σ_s^2 受地形因素影响。文献 [6] 综合基站发射功率、移动台接收灵敏度以及无线传播环境的影响，给出 $m(x)$ 的基本模型并被广泛应用，表示为式（1–4）

$$M(x) = K_1 + K_2 \log(x) \tag{1–4}$$

其中 $M(x) := 20\log(m(x))$ 为 $m(x)$ 的对数形式，K_1 主要与基站发射功率、天线增益及线路损耗有关，K_2 为地形因子并随着无线传播环境的不同而变化 [7][8]。$S(x)$ 的空间相关性，即其自相关函数，主要与地形因素有关，表示为式（1–5）[9]。

$$R_s(x) = \sigma_s^2 \exp\left(-\frac{\Delta x}{x_0}\right) \tag{1–5}$$

其中 σ_s 为 $S(x)$ 的方差，通常在 4 到 12dB 间取值；x_0 为相关距离，根据传播环境的不同一般为 10m 到 500m [10]；Δx 为相对距离，可以通过移动台运行速度即采样时间间隔获得，即 $\Delta x = v_{train} \cdot \Delta t$。在阴影衰落模型中，地形因子 K_2、阴影衰落方差 σ_s 及自相关距离 x_0 都与无线传播环境有关，同时影响到上层应用的参数设置，例如小区切换算法中的切换门限值的选择。

1.2.2 多径衰落

多径衰落是由于信号的衍射和散射而导致的接收信号强度的瞬时波动，所以移动终端的接收信号强度是来自不同方向信号的叠加。由于信号的相位是随机的，因此可以描述为本地均值与噪声信号的总和。由于 GSM-R 网络的小区半径通常较短，同时无线传播环境一般是平坦的地形，因此多路径衰落包含一个可视 LOS 信号，此时多径衰落可以刻画为莱斯衰落，表示为可视 LOS 信号与非直射 NLOS 信号的叠加，如式（1–6）所示，

$$h(x) = \underbrace{\frac{1}{\sqrt{1+K}} \lim_{M\to\infty} \frac{1}{\sqrt{M}} \sum_{m=1}^{M} a_m e^{j(\frac{2\pi}{\lambda}\cos(\theta_m x)+\phi_m)}}_{\text{NLOS Components}} + \underbrace{\sqrt{\frac{K}{1+K}} e^{j(\frac{2\pi}{\lambda}\cos(\theta_0 x+\phi_0))}}_{\text{LOS Component}} \tag{1–6}$$

其中 M 散射信号数量，λ 为信号波长，$\theta_m(m=0,1,...M)$ 代表不同信号与接收移动终端间夹角，$\phi_m(m=0,1,...M)$ 为每路信号的相位。在莱斯衰落中，直射路径与非直射路径信号强度分别表示为 ν^2 和 $2\sigma^2$，则 K 表示直射路径信号与其他路径信号的比值，即 $K=\nu^2/2\sigma^2$，此时接收信号幅值服从参数为 ν^2 和 σ^2 的莱斯分布，其概率分布函数（Probability Distribution Function, PDF）表示为

$$f(y;\sigma,\nu)=\frac{y}{\sigma^2}e^{-\frac{y^2+\nu^2}{2\sigma^2}}I_0\left(\frac{y\nu}{\sigma^2}\right) \tag{1–7}$$

其中 $I_0(\cdot)$ 零阶第一类修正贝塞尔函数。当不存在直射路径信号，即 $K=0$ 时，莱斯衰落退化为瑞利衰落，此时接收信号幅值的概率分布函数简化为

$$h(x)=\lim_{M\to\infty}\frac{1}{\sqrt{M}}\sum_{m=1}^{M}a_m e^{j\left(\frac{2\pi}{\lambda}\cos(\theta_m x)+\phi_m\right)} \tag{1–8}$$

$$f(y;\sigma)=\frac{y}{\sigma^2}e^{-\frac{y^2}{2\sigma^2}} \tag{1–9}$$

1.3 信道状态动态估计

由于 GSM-R 网络负责为高速铁路提供无线通信，因此需要在线实时测试以保证通信网络与高铁系统的安全可靠运行，本文提出接收信号强度在线动态测试算法，以提高信道状态测试的精度并降低其开销。

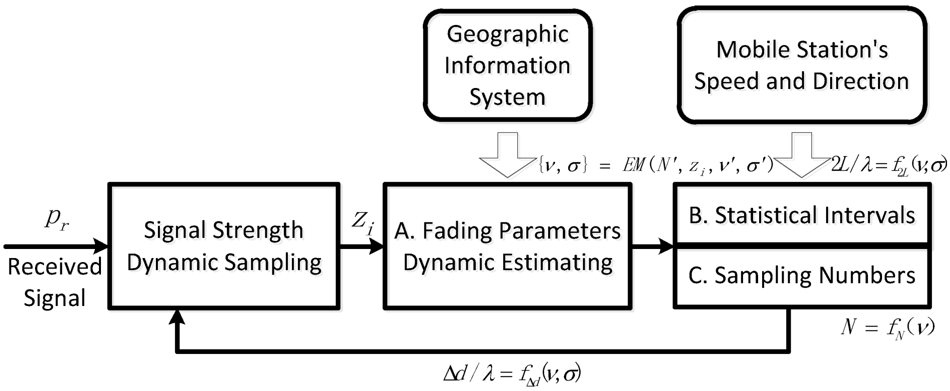


图 1–6 在线动态测试框架

Fig 1–6 On-line and Dynamic Estimation of Rician Fading Channels

动态测试算法的工作过程如图 1–6 所示，首先对信号进行动态采样，得到一组当前时刻的信号强度值，然后经过衰落参数动态估计，得到当前无线传播

环境的莱斯衰落参数，然后经过计算得到统计区间与采样点数，同时以此为基础开始下一次信号采样。

1.3.1 信道参数估计

对于莱斯衰落信道的参数估计已有大量相关工作，包括基于学习训练机制 [3]、最大似然估计（Maximum Likelihood, ML）[4] 以及期望最大化算法（Expectation Maximization, EM）[5]。由于 EM 算法通过迭代方式进行参数估计，本文采用 EM 算法进行莱斯参数估计，以充分利用历史信息提高测试精度并降低测试开销。EM 算法中莱斯衰落因子 ν^2 和 σ^2 通过其上一时刻估计值与当前采样信号计算获得，如式（1–10）所示

$$\nu_{k+1} = \frac{1}{N}\sum_{i=1}^{N}\frac{I_1\left(\frac{\nu_k z_i}{\sigma_k^2}\right)}{I_0\left(\frac{\nu_k z_i}{\sigma_k^2}\right)}z_i \tag{1–10a}$$

$$\sigma_{k+1}^2 = \max\left[\frac{1}{2N}\sum_{i=1}^{N}z_i^2 - \frac{\nu_k^2}{2}, 0\right] \tag{1–10b}$$

其中 $I_1(\cdot)$ 一阶第一类修正贝塞尔函数，N 为采样信号数码，ν_k 和 σ_k 为上一时刻估计结果，其初始值为

$$\nu_0 = \left(2\left(\frac{1}{N}\sum_{i=1}^{N}z_i^2\right)^2 - \frac{1}{N}\sum_{i=1}^{N}z_i^4\right)^{1/4} \tag{1–11a}$$

$$\sigma_0^2 = \frac{1}{2}\left(\frac{1}{N}\sum_{i=1}^{N}z_i^2 - \nu_0\right) \tag{1–11b}$$

基于以上的莱斯衰落参数估计，接收信号强度测试的采样频率可以计算得到，表示为信号波长 λ 与衰落参数 ν 和 σ 的函数。采样频率 Δd 通过统计区间长度 $2L$ 与采样点数目 N 的比值计算而来。

1.3.2 统计区间长度

对于第 1.2 节的无线传播模型，接收信号强度的本地均值通过对采样信号 $p_r(x)$ 在统计区间 $2L$ 内进行积分平均获得，即

$$\hat{s} = \frac{1}{2L}\int_{y-L}^{y+L} p_r^2(x)dx = \frac{s}{2L}\int_{y-L}^{y+L} h(x)dx \tag{1–12}$$

如果能够选取合适的统计区间长度 $2L$，则估计值 $\hat{s}$ 将逼近其实际值 s，即 $\hat{s} \to s$，此时小尺度衰落的均值表示为

$$\frac{1}{2L}\int_{y-L}^{y+L} h(x)dx \to 1 \tag{1–13}$$

由式（1–12）可知，估计值 $\hat{s}$ 相对于真实值 s 的误差可以由 $\hat{s}$ 的方差衡量，如式（1–14）所示

$$\sigma_{\hat{s}}^2 = \frac{1}{L}\int_{0}^{2L}\left(1-\frac{\tau}{2L}\right)R_{p_r^2}(\tau)d\tau \tag{1–14}$$

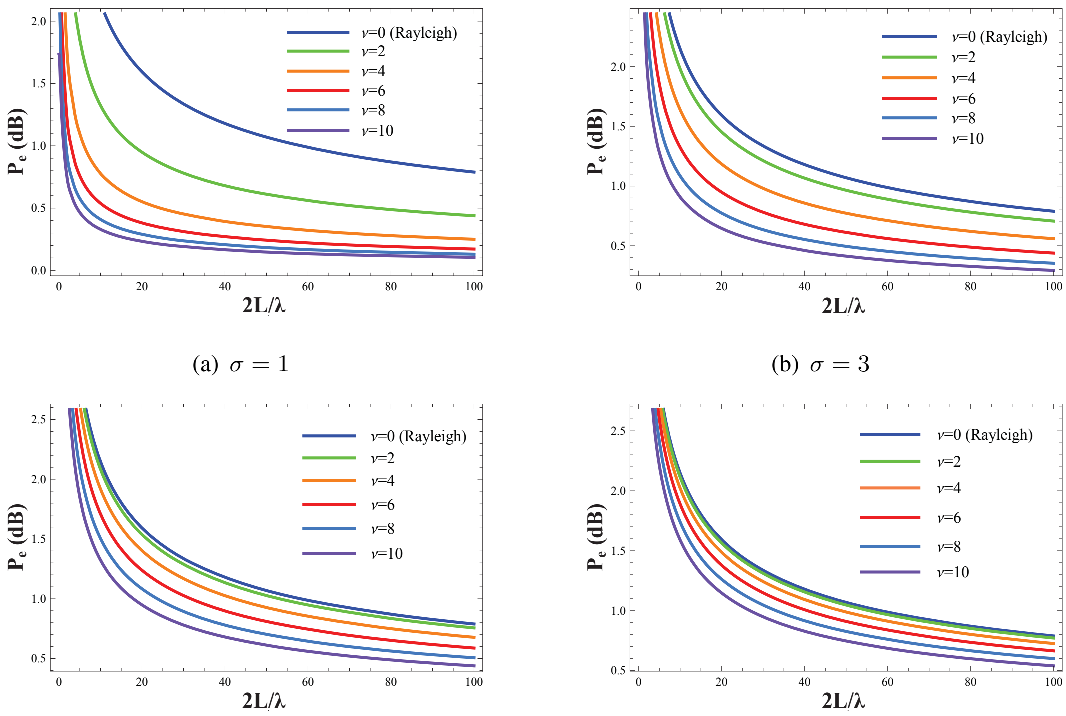
其中 $R_{p_r^2}(\tau) = E[p_r^2(x)p_r^2(x+\tau)] - E[p_r^2(x)]E[p_r^2(x+\tau)]$ 为包络信号 $p_r(x)$ 的自相关函数。则估计值 $\hat{s}$ 的均一化误差可以表示为

$$P_e := 10\log_{10}\left(\frac{\hat{s}+\sigma_{\hat{s}}}{\hat{s}-\sigma_{\hat{s}}}\right) \tag{1–15}$$

将式（1–12）和式（1–14）带入式（1–15）中，并按照附录A.1求解积分方程，归一化误差 P_e 可以表示为

$$P_e = 10\log_{10}\left(\frac{\frac{2\sigma^2+\nu^2}{2\sigma^2}n + \sqrt{2(1+n)\int_0^n g\left(\frac{\nu^2}{2\sigma^2};\rho\right)d\rho}}{\frac{2\sigma^2+\nu^2}{2\sigma^2}n - \sqrt{2(1+n)\int_0^n g\left(\frac{\nu^2}{2\sigma^2};\rho\right)d\rho}}\right) \tag{1–16}$$

其中 ν 和 σ 为莱斯衰落信道参数。令归一化误差等于 1，即 $P_e = 1dB$，则可以得到合适的统计区间长度 $2L$ 与信号波长 λ 及衰落参数 ν^2 和 σ^2 的关系式，即 $2L = f_{2L}(\lambda;\nu,\sigma)$ 或 $2L/\lambda = f_{2L/\lambda}(\nu,\sigma)$，如图 1–7 所示。



(a) $\sigma = 1$ (b) $\sigma = 3$

(c) $\sigma = 5$ (d) $\sigma = 7$

图 1–7 统计区间长度

Fig 1–7 Proper Length of Statistical Intervals

1.3.3 采样点数

除了选择合适的统计区间长度外，还需要确定采样点数目，以有效降低多径衰落对信号估计的影响。采样得到的接收信号功率可以通过衰落参数计算得到，结合式（1–10）有 $r^2 = 2\sigma^2 + \nu^2 \approx \frac{1}{N}\sum_{i=1}^{N} z_i^2$，则 r^2 的估计值及其方差为

$$\bar{r^2} = E\left[r^2\right] = \frac{1}{N}E\left[\sum_{i=1}^{N} z_i^2\right] \tag{1–17a}$$

$$\sigma_{\bar{r^2}} = D\left[r^2\right] = \frac{1}{N^2}D\left[\sum_{i=1}^{N} z_i^2\right] \tag{1–17b}$$

与统计区间长度的归一化误差类似，采样点数目的归一化误差为

$$Q_e = 10\log_{10}\left(\frac{\bar{r^2} + \sigma_{\bar{r^2}}}{\bar{r^2}}\right) \tag{1–18}$$

根据附录 A.2 中的计算与推导，Q_e 可以表示为

$$Q_e = 10\log_{10}\left(\frac{2N+\nu^2+2\sqrt{N+\nu^2}}{2N+\nu^2}\right) \tag{1–19}$$

其中 ν 和 σ 为莱斯衰落参数，通过如式（1–10）中 EM 算法计算得到。显然采样点数目只与莱斯衰落参数 ν 有关，即 $N = f_N(\nu)$，如图 1–8 所示。

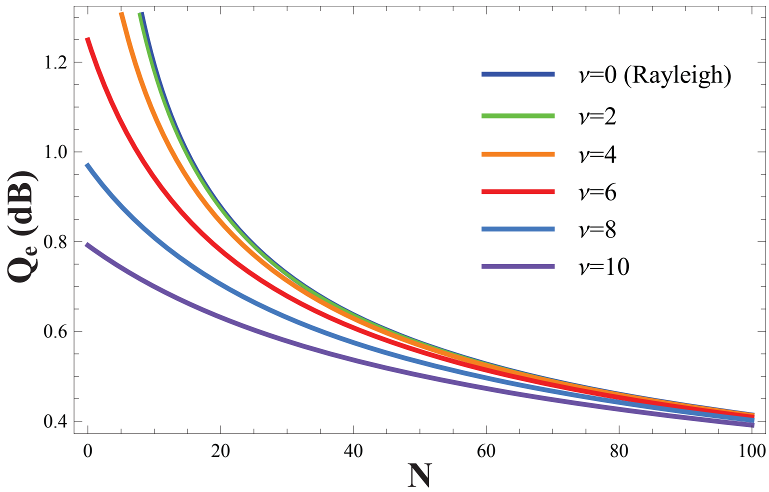


图 1–8 采样点数

Fig 1–8 Required Number of Averaging Samples

接收信号强度采样频率 Δd 由 $2L/N$ 计算获得，即 $\Delta d = f_{2L}(\lambda;\nu,\sigma)/f_N(\nu) = f_{\Delta d}(\lambda;\nu,\sigma)$。由于信号波长 λ 在通信过程中一般保持不变，因此 Δd 与莱斯衰落参数 ν 和 σ 密切相关。

1.4 系统实现

GSM-R 网络通信质量测试系统主要完成物理指标的实时测量，同时对网络链路质量进行统计与分析，包括实时测试与离线分析。GSM-R 网络空中接口测试系统实现对 GSM-R 网络通信质量的在线实时与离线综合测试，如图 1–9 所示。在线测试实现对 GSM-R 网络通信质量的实时监测，同时在网络出现故障时给出预警信息；离线测试对 GSM-R 网络性能进行统计与分析，给出网络的综合性能评估，并提出参数调整建议。同时测试指标包含网络物理层、

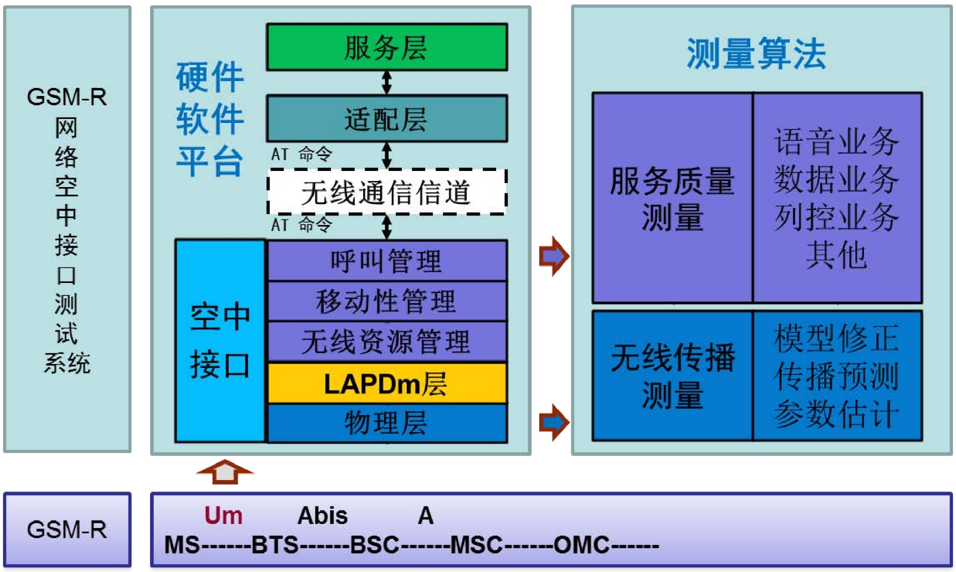


图 1–9 GSM-R 网络空中接口测试系统
Fig 1–9 Um interface monitoring system for GSM-R networks

链路层与业务层各项指标，实现对 GSM-R 网络通信质量的全面测试，保证高铁系统的安全稳定高速运行。

本章首先引入 GSM-R 网络空中接口测试系统的基本结构，包括硬件平台与软件开发，然后分析动态测试算法的设计与实现，最后对系统的基本功能进行简单介绍。

1.4.1 硬件平台

GSM-R 网络测试系统由无线收发模块、通信协议处理模块、数据分析处理模块构成，如图 1–10 所示，其中无线收发模块完成 GSM-R 网络通信信号采集，通信协议处理模块主要对采集到的网络信令进行解析，数据分析处理模块负责对网络各项性能指标进行统计与分析。

测试系统中心处理器模块为美国 RTD 公司的 CME137686LX-W cpuModules™，通信协议处理模块与射频收发模块选择德国 Triorail 公司的 GSM-R 网络收发模块 TRM:3a，外加 RTD 公司的 GSM-R 网络收发模块外围开发板 COM16155RER-1，上述模块通过 PC/104 与 RTD 的电源模块 VPWR104HR-L50W 相连接，从而实现 GSM-R 网络信息收发功能。

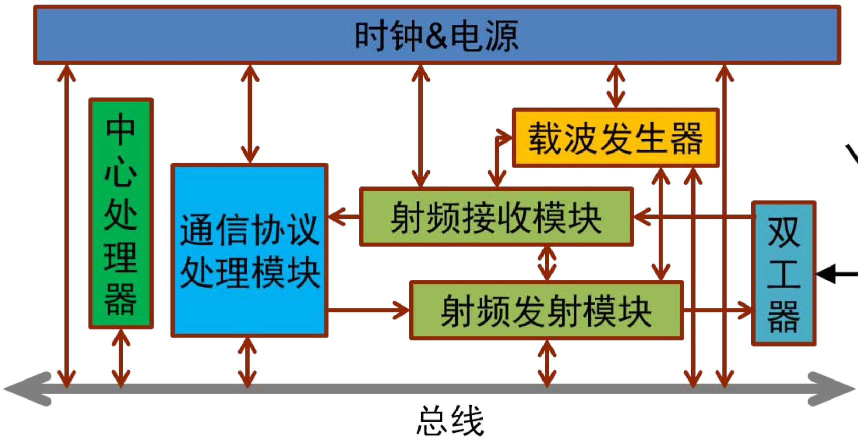


图 1–10 GSM-R 网络空中接口测试系统硬件组成

Fig 1–10 Hardware components of Um interface monitoring system for GSM-R networks

GSM-R 网络空中接口测试系统的硬件平台由 PC/104 总线实现模块间通信，主要由以下三部分组成:

- **处理器模块** 处理器模块采用 RTD 公司符合军工标准的 CME137686LX-W 模块，该模块采用 500MHz AMD™ Geode LX 处理器，具有 128kB L1 缓存和 128kB L2 缓存，采用 333MHz DDR-SDRAM 控制器支持最高 2.7G-Bytes/s 的存储带宽，包括 4 个 USB 2.0 接口, 2 个 SATA II 接口, 3 个串口、千兆以太网口、8GB 板贴固态硬盘和 8 个 GPIO，在有效完成数据处理的同时，满足高速铁路复杂的无线传播环境。

- **无线通信模块**　COM16155ER 模块板载 Cinterion 4 频段 GSM/GPRS 模块 MC55i 和 Fastrax IT500 GPS 模块，在实际测试过程中，将 GSM 模块替换为德国 Triorail 公司的 GSM-R 收发模块 TRM:3a。COM16155ER 板载两个 ISA 总线接口的 UART，分别连接到 GSM-R 模块和 GPS 模块，主机模块通过 UART 和相关接口对 GSM-R 模块和 GPS 模块进行操作。

- **电源模块** 电源模块采用 RTD 的电源模块 VPWR104HR-L50W，输入电压 20-28VDC，输出电压 -12V 到 +19V，工作温度 -40 到 +85C○，能够满足高速铁路的特殊环境要求。

上述各模块符合工业级标准，性能稳定并能够工作在各种恶劣环境，同时 PC/104 作为工业级总线能够保证系统的实时性与可靠性。

1.4.2 软件开发

GSM-R 网络空中接口测试软件平台的开发基于 Visual Studio 2008 开发环境，开发语言为 C#，软件运行平台为 Windows XP、Windows Mobile 或 Windows CE 操作系统，运行环境 Microsoft .NET Compact Framework 2.0 或者以上版本，测试系统的启动和运行界面如图 1–11 和图 1–12 所示。

图 1–11 GSM-R 网络空中接口测试系统启动界面

Fig 1–11 Software starting of Um interface monitoring system for GSM-R networks

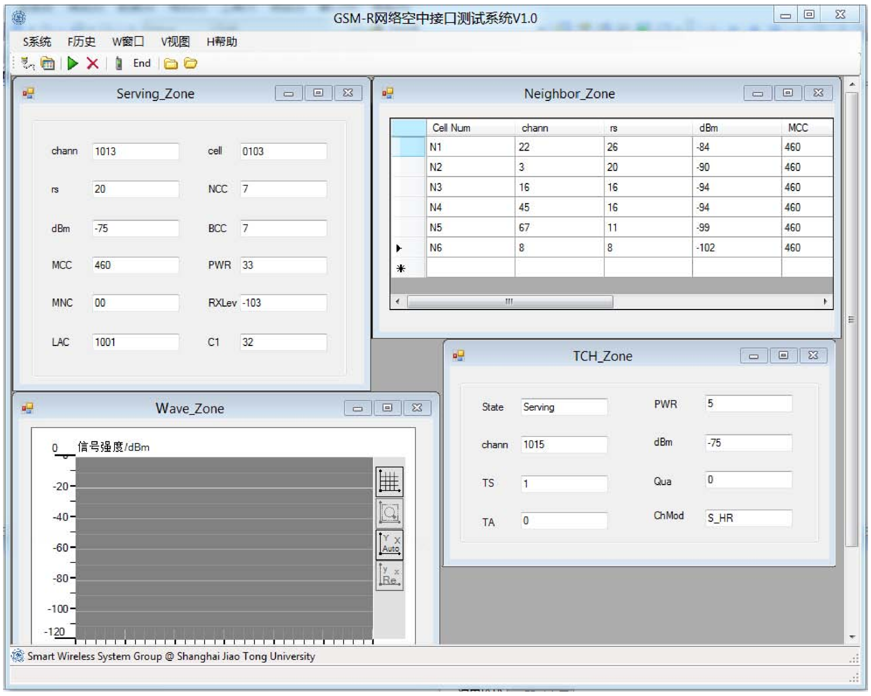


图 1–12 GSM-R 网络空中接口测试系统软件界面

Fig 1–12 Software interface of Um interface monitoring system for GSM-R networks

1.4.3 算法实现

GSM-R 网络接收信号强度在线测试的伪代码如算法 1 所示，主要基于第 1.3 章的推导与计算。首先通过 EM 算法进行莱斯衰落参数估计，实现莱斯衰落因子 ν_0 和 σ_0 的初始化，此时的信号采样参数去瑞利衰落时的参数设置，即统计区间 $2L = 40\lambda$，采样点数 $N = 36$。然后在每一轮采样周期基于上一轮估计结果和当前采样信息，对衰落因子 ν_k 和 σ_k 进行实时更新，同时确定下一轮采样参数 $2L$ 和 N。最后通过统计区间长度和采样点数计算得到采样间隔 $\Delta d = 2L/N$，并开始新一轮的信号采样与参数估计。

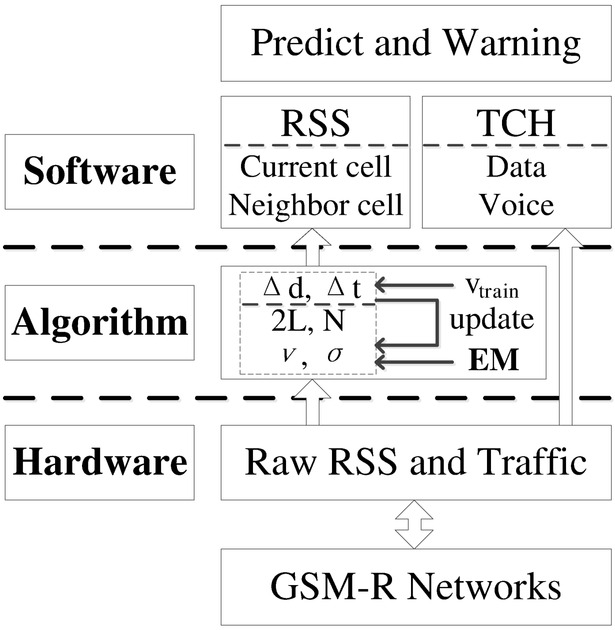


图 1–13 信道状态估计算法与实现

Fig 1–13 Estimation framework and algorithm implementation

GSM-R 网络信道动态测试为上层应用提供准确的网络状态信息，如图 1–13 所示，测试系统首先通过 GSM-R 收发模块，获得接收信号强度的原始信息；然后由动态采样算法进行数据处理与参数估计，并提供当前网络状态信息，包括物理层信道状态与链路质量信息；同时系统根据历史信息对网络状态进行预测，在信号强度持续下降时给出预警信息；最后动态测试算法将所有原始数据及网络状态信息提供给软件界面及数据库，用于显示当前网络状态信息，或进行网络性能的分析与评估，包括切换性能分析与网络优化。

算法 1 莱斯衰落信道在线采样与估计

输入： v_{train}, r_i, ν_k, σ_k

输出： ν_{k+1}, σ_{k+1}, $2L$, N, Δd

// 1. 衰落参数 ν 和 σ 初始化
if begin-flag==true **then**
  $\Delta d \leftarrow$ Lee($2L_0$,N_0;λ);
  $\{\nu_{last}, \sigma_{last}\} \leftarrow$ EM(Δd,N_0;r_i); // 式（1–11）
  $\{\nu_{now}, \sigma_{now}\} \leftarrow$ EM(Δd,N_0;r_i;ν_{last},σ_{last}); // 式（1–10）
  while $(\nu_{now} - \nu_{last} > \nu_{thr})$ & $(\sigma_{now} - \sigma_{last} > \sigma_{thr})$ **do**
    $\{\nu_{next}, \sigma_{next}\} \leftarrow$ EM(Δd,N_0;r_i;ν_{now},σ_{now}); // 式（1–10）
    $\{\nu_{last}, \sigma_{last}\} \leftarrow \{\nu_{now}, \sigma_{now}\}$;
    $\{\nu_{now}, \sigma_{now}\} \leftarrow \{\nu_{next}, \sigma_{next}\}$;
  end while
  $2L_{now} \leftarrow f_{2L}(\lambda; , \nu_{now}, \sigma_{now})$; // 式（1–16）
  $N_{now} \leftarrow f_N(\nu_{now})$; // 式（1–19）
end if
// 2. ν 和 σ 实时估计，计算采样参数 $2L$、N 和 Δd.
if operating-flag==true **then**
  for $i = 0; i < N_{now}; i++$ **do**
    $\{\nu_{next}, \sigma_{next}\} \leftarrow$ EM(Δd,N_0;r_i;ν_{now},σ_{now}); // 式（1–10）
    $2L_{next} \leftarrow f_{2L}(\lambda; , \nu_{now}, \sigma_{now})$; // 式（1–16）
    $N_{next} \leftarrow f_N(\nu_{now})$; // 式（1–19）
    $\Delta d_{next} = f_{2L}(\lambda; , \nu_{now}, \sigma_{now}) / f_N(\nu_{now})$;
    $\{\nu_{last}, \sigma_{last}; 2L_{last}, N_{last}\} \leftarrow \{\nu_{now}, \sigma_{now}; 2L_{now}, N_{now}\}$;
    $\{\nu_{now}, \sigma_{now}; 2L_{now}, N_{now}\} \leftarrow \{\nu_{next}, \sigma_{next}; 2L_{next}, N_{next}\}$;
    if $i == N_{last}$ **then**
      i=0;
    end if
  end for
end if

1.4.4 基本功能

GSM-R 网络空中接口测试系统的基本功能如图 1–14 所示，主要完成网络通信质量的测试、处理、预测、显示与预警。

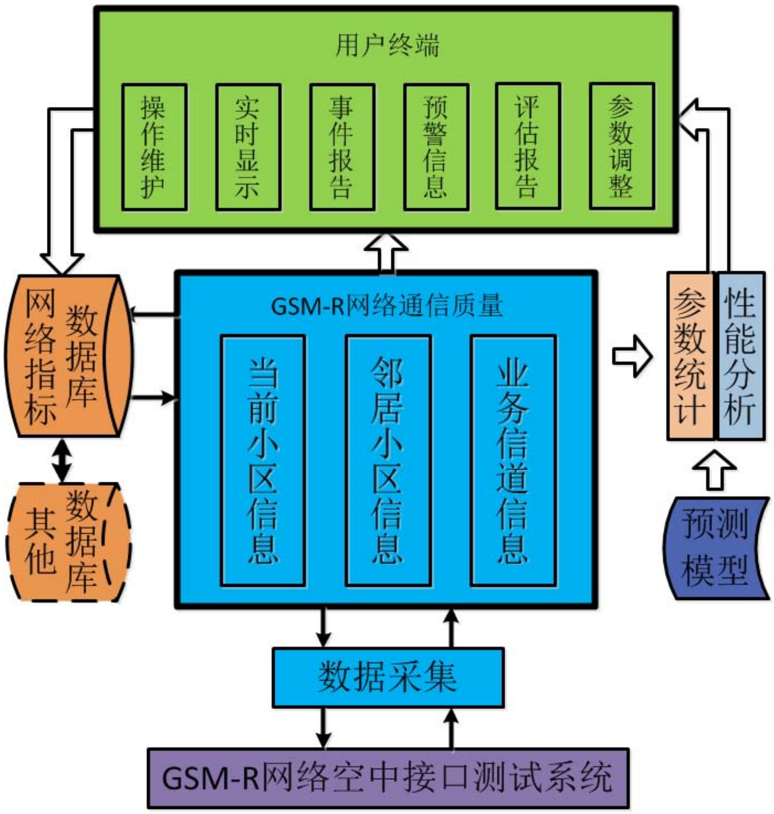


图 1–14 GSM-R 网络空中接口测试系统软件结构

Fig 1–14 Software architecture of Um interface monitoring system for GSM-R networks

测试系统在硬件配置完成后，测试软件首先对 GSM-R 网络空中接口传输的信息进行解析，得到网络当前时刻与位置的通信质量信息，并根据 GSM-R 网络当前小区信息得到网络当前广播控制信道、语音业务信道和数据域业务信道质量信息，并给出小区切换和信道切换的分布图，同时绘制当前服务小区广播控制信道的接收信号强度和邻居小区广播控制信道接收信号质量的曲线轨迹，利用当前测试数据与历史数据，结合预测模型对网络的无线传播进行预测，在当前网络通信质量低于系统要求时给出警告信息，结合地理信息和基站信息，给出测试报告并对 GSM-R 网络性能进行整体评估。

- 当前小区信息：显示移动台当前所在小区基本信息，包括小区编号、信道编号、接收信号强度、基站识别码、功率等级和小区重选系数等信息。
- 邻居小区信息：显示接收信号强度最好的三个到六个邻居小区的信息，包括信道编号、接收信号强度、基站识别码和小区重选系数等。
- 业务信道信息：显示当前业务信道基本信息，包括信道编号、时隙分配、时间提前量、功率大小、接收信号强度、接收信号质量和信道模式等。
- 曲线绘制：实时记录当前小区及邻居小区的接收信号强度信息，并能够调取历史数据和数据库中的数据，进行场景重现。
- 历史数据：导入或导出历史数据，实现对任意时刻的通信情况进行分析，为 GSM-R 网络的优化提供数据支持。

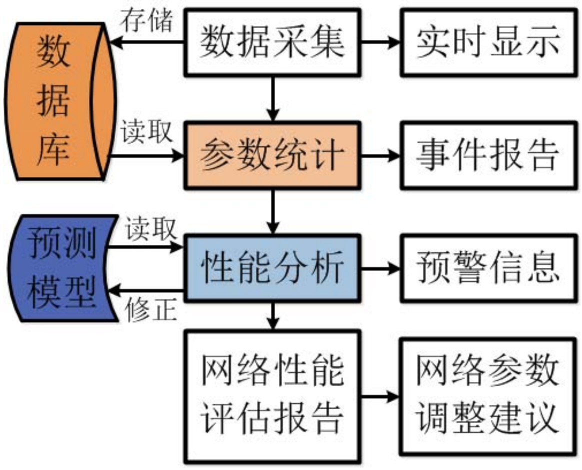
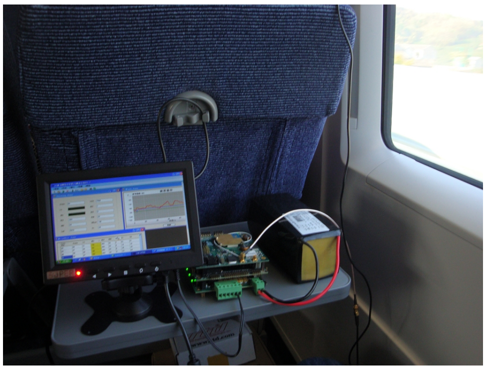


图 1–15 GSM-R 网络空中接口测试系统数据处理

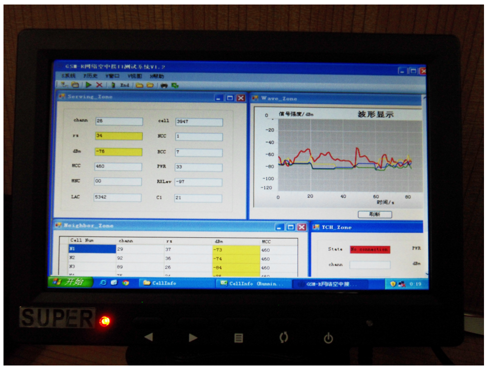
Fig 1–15 Data processing of Um interface monitoring system for GSM-R networks

1.5 性能评估

本节主要介绍动态测试算法的实验分析与性能评估，通过 GSM-R 网络空中接口测试系统，由高速列车上的移动终端在京沪高速铁路沿线进行接收信号强度信息采集，如图 1–16 所示。



(a) 硬件平台

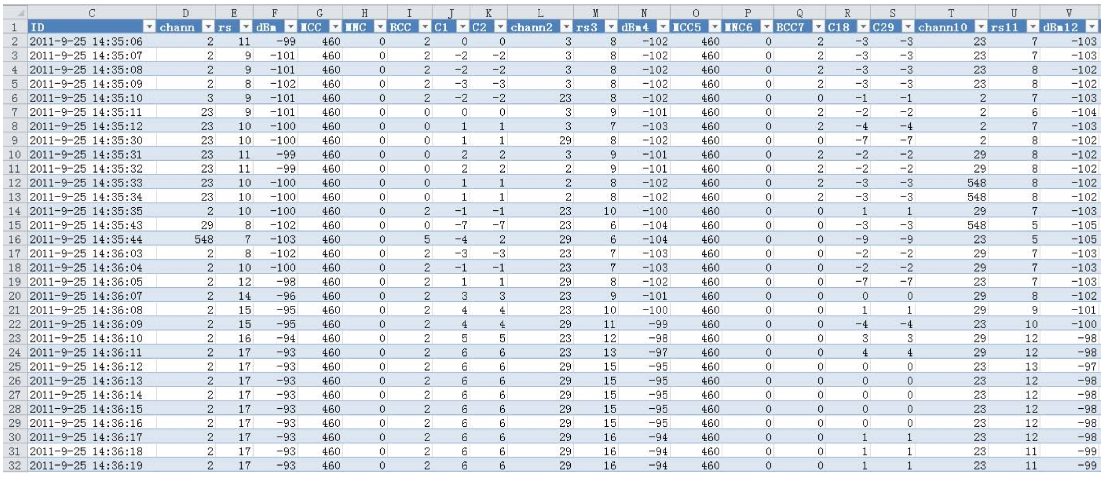


(b) 软件平台

图 1–16 GSM-R 网络空中接口测试系统

Fig 1–16 Um Interface Monitoring System for GSM-R Networks

实验测试结果以 XML 格式进行存储与处理，如图 1–17 所示为京沪高铁 GSM-R 网络接收信号强度信息。动态估计算法的测试结果如表 1–1 所示，包括不同无线传播环境下的莱斯衰落参数与采样参数，其中无线传播类型由莱斯衰落参数 K 表示：当 $K = 0$ 时表示没有直射路径信号，此时莱斯衰落退化为瑞利衰落；当 K 逐步增加表示无线传播环境逐渐平坦。



	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	ID	chann	rs	dBm	MCC	MNC	BCC	C1	C2	chann2	rs3	dBm4	MCC5	MNC6	BCC7	C18	C29	chann10	rs11	dBm12
2	2011-9-25 14:35:06	2	11	-99	460	0	2	0	0	3	8	-102	460	0	2	-3	-3	23	7	-103
3	2011-9-25 14:35:07	2	9	-101	460	0	2	-2	-2	3	8	-102	460	0	2	-3	-3	23	7	-103
4	2011-9-25 14:35:08	2	9	-101	460	0	2	-2	-2	3	8	-102	460	0	2	-3	-3	23	8	-102
5	2011-9-25 14:35:09	2	8	-102	460	0	2	-3	-3	3	8	-102	460	0	2	-3	-3	23	8	-102
6	2011-9-25 14:35:10	3	9	-101	460	0	2	-2	-2	23	8	-102	460	0	0	-1	-1	2	7	-103
7	2011-9-25 14:35:11	23	9	-101	460	0	0	0	0	3	9	-101	460	0	2	-2	-2	2	6	-104
8	2011-9-25 14:35:12	23	10	-100	460	0	0	1	1	3	7	-103	460	0	2	-4	-4	2	7	-103
9	2011-9-25 14:35:30	23	10	-100	460	0	0	1	1	29	8	-102	460	0	0	-7	-7	2	8	-102
10	2011-9-25 14:35:31	23	11	-99	460	0	0	2	2	3	9	-101	460	0	2	-2	-2	29	8	-102
11	2011-9-25 14:35:32	23	11	-99	460	0	0	2	2	2	9	-101	460	0	2	-2	-2	29	8	-102
12	2011-9-25 14:35:33	23	10	-100	460	0	0	1	1	2	8	-102	460	0	2	-3	-3	548	8	-102
13	2011-9-25 14:35:34	23	10	-100	460	0	0	1	1	2	8	-102	460	0	2	-3	-3	548	8	-102
14	2011-9-25 14:35:35	2	10	-100	460	0	2	-1	-1	23	10	-100	460	0	0	1	1	29	7	-103
15	2011-9-25 14:35:43	29	8	-102	460	0	0	-7	-7	23	6	-104	460	0	0	-3	-3	548	5	-105
16	2011-9-25 14:35:44	548	7	-103	460	0	5	-4	2	29	6	-104	460	0	0	-9	-9	23	5	-105
17	2011-9-25 14:36:03	2	8	-102	460	0	2	-3	-3	23	7	-103	460	0	0	-2	-2	29	7	-103
18	2011-9-25 14:36:04	2	10	-100	460	0	2	-1	-1	23	7	-103	460	0	0	-2	-2	29	7	-103
19	2011-9-25 14:36:05	2	12	-98	460	0	2	1	1	29	8	-102	460	0	0	-7	-7	23	7	-103
20	2011-9-25 14:36:07	2	14	-96	460	0	2	3	3	23	9	-101	460	0	0	0	0	29	8	-102
21	2011-9-25 14:36:08	2	15	-95	460	0	2	4	4	23	10	-100	460	0	0	1	1	29	9	-101
22	2011-9-25 14:36:09	2	15	-95	460	0	2	4	4	29	11	-99	460	0	0	-4	-4	23	10	-100
23	2011-9-25 14:36:10	2	16	-94	460	0	2	5	5	23	12	-98	460	0	0	3	3	29	12	-98
24	2011-9-25 14:36:11	2	17	-93	460	0	2	6	6	23	13	-97	460	0	0	4	4	29	12	-98
25	2011-9-25 14:36:12	2	17	-93	460	0	2	6	6	29	15	-95	460	0	0	0	0	23	13	-97
26	2011-9-25 14:36:13	2	17	-93	460	0	2	6	6	29	15	-95	460	0	0	0	0	23	12	-98
27	2011-9-25 14:36:14	2	17	-93	460	0	2	6	6	29	15	-95	460	0	0	0	0	23	12	-98
28	2011-9-25 14:36:15	2	17	-93	460	0	2	6	6	29	15	-95	460	0	0	0	0	23	12	-98
29	2011-9-25 14:36:16	2	17	-93	460	0	2	6	6	29	15	-95	460	0	0	0	0	23	12	-98
30	2011-9-25 14:36:17	2	17	-93	460	0	2	6	6	29	16	-94	460	0	0	1	1	23	12	-98
31	2011-9-25 14:36:18	2	17	-93	460	0	2	6	6	29	16	-94	460	0	0	1	1	23	11	-99
32	2011-9-25 14:36:19	2	17	-93	460	0	2	6	6	29	16	-94	460	0	0	1	1	23	11	-99

图 1–17 信道状态测试结果

Fig 1–17 Measurement Results

从表 1–1 中的数据可以看出，在莱斯因子 $K = 0$ 时，统计区间为 $2L = 40\lambda$，采样间隔为 $\Delta d = 0.5\lambda$；随着莱斯因子 K 的增大，无线传播环境逐渐平

坦，导致直射路径功率比例增加，统计区间与采样间隔逐渐降低；当 $\nu \geq 8$ 时所需的采样点数 $N \leq 10$，即在不同统计区间内只需做 $N \leq 10$ 次采样，便可以保证本地均值的准确性，同时在 K 值逐渐增大过程中，统计区间相应增大，且不需要做频繁的数据采集，采样间隔在 $1m$ 左右。

表 1–1 信道状态估计结果总结

Table 1–1 Summary of Experiment Results of Channel State Estimation

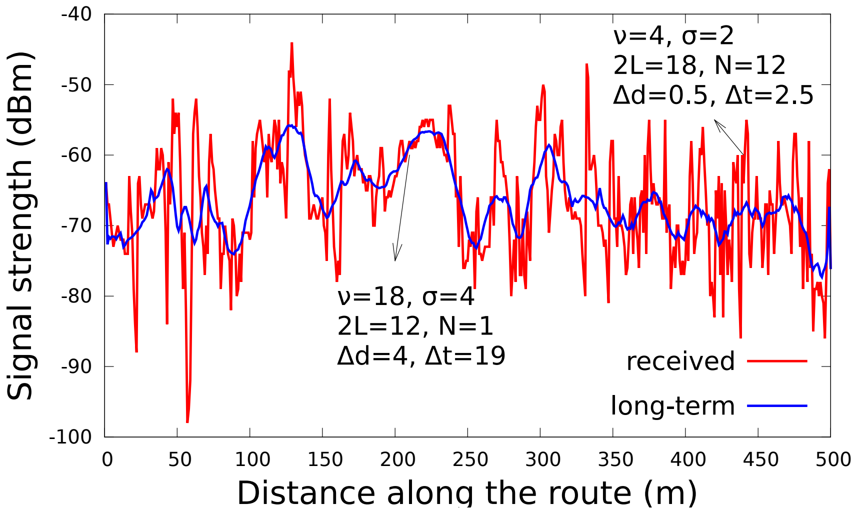
Terrain	K(dB)	ν	σ	$2L/\lambda$	N	$\Delta d/\lambda$	Δd(m)	v_{train}(km/h) 200	250	300
								Δt(ms)		
NLOS*	0	-	-	40	36	1.1	0.367	2.20	1.76	1.47
Dense	0	0	1	55	15	3.7	1.222	7.33	5.86	4.89
	2	4	2	18	12	1.5	0.500	3.00	2.40	2.00
	4	5.6	2	9	9	1.0	0.333	2.00	1.60	1.33
	6	6	3	20	7	2.9	0.967	5.80	4.64	3.87
	8	12	3	8	1	8.0	2.667	16.00	12.80	10.67
Open	10	18	4	12	1	12.0	4.000	24.00	19.20	16.00

* Caculated by Lee's method of local mean power estimation in the case of Rayleigh fading

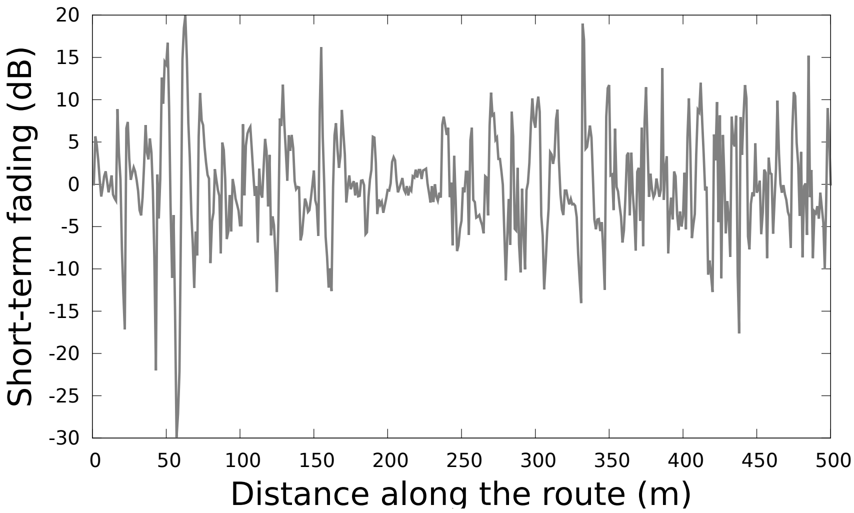
The measurement results is demonstrated in Fig. 1.18(a), and the long-term and short-term fading are separated after on-line propagation estimation. As is shown in Fig. 1.18(b), the long-term and short-term fading are differentiated so that they can be analyzed separately. The long-term parts can be used to make propagation prediction by Maximum Likelihood (ML) or Minimum Mean Square Error (MMSE) estimator. On the other hand, the short-term variations are essential to the section of the hysteresis in handoff algorithms.

1.6 本章小结

本章讨论了在莱斯衰落环境下，GSM-R 网络接收信号强度的动态采样算法，该算法通过采样数据结合衰落参数历史值，对当前衰落参数进行估计，确定不同衰落参数条件下的统计区间与采样点数。在城区、山地、丘陵等密集区域，由于多径衰落现象加重，且直射路径功率所占比例较低，需要进行较为频



(a) 接收信号强度与大尺度衰落



(b) 小尺度衰落

图 1–18 接收信号强度与信号衰落

Fig 1–18 Received signal strength and signal fading

繁的采样与统计，确保统计区间 $2L \leq 20m$，采样间隔 $\Delta d \leq 0.3m$；在平原、高架桥等开阔区域，移动台接收功率较大，且一般存在较大比例的直射路径功率，在同样的统计区间内只需做较少的采样，保证统计区间 $2L \leq 50m$，采样间隔 $\Delta d \leq 1.5m$，便可以满足本地均值的准确性要求。对应列车运行速度在 $300km/h$ 时，采样时间间隔为 $2.0ms$ 到 $18.0ms$ 时，才能够保证测量数据的可靠性。在实际工程应用中的 GSM-R 网络无线覆盖测量，一般采用采样间隔 $\Delta d = 4cm$、统计区间 $10m \leq 2L \leq 100m$ 的方法，参照本章关于莱斯衰落信道下采样算法的推导，可以在高铁线路中的开阔区域适当提高采样间隔，从而在确保数据可靠性的同时降低测量开销；另一方面针对 GPS 测距触发方式的测量方法，利用高速铁路列车运行速度相对固定的特点，结合列车运行速度、当前采样数据及衰落参数历史数据，采用时间触发的方式进行采样间隔与统计区间的确定。

全文总结

This paper proposed the on-line and dynamic estimation algorithm of Rician fading channels in GSM-R networks, which is influential in system's real-time reliability. We gave the basic procedure of this algorithm which is similar to the Lee's standard procedure except that the multi-path fading channel is Rician distributed, for the cell radius is designed short and the terrain is generally flat in GSM-R networks. Then we discussed the determination of proper length of statistical interval and required number of averaging samples, in which EM method is employed to reduce the estimating overhead and make the measurement adaptive to different propagation environments. To evaluate the performance of the algorithm, measurement experiment was implemented along the Beijing-Shanghai high-speed railway. It is illustrated that the long-term and short-term fading can be differentiated separately by the on-line estimating algorithm. In the end, the experiment results were summarized and compared to the Lee's local power estimating method. It requires smaller sampling intervals in Lee's method than that of on-line method when it is NLOS propagation, which can be increased from 1.1λ to 3.7λ. It does not need to make frequent sampling although the length of statistical interval decreases when there is LOS signal, it can be set up to 12λ to reduce the measurement overhead. The on-line and dynamic estimation algorithm can be not only used in coverage assessment with lower measurement overhead which is implemented in network planning, but also applied in real-time dynamic channel allocation, power control and adaptive handoff algorithms. Since Rician fading is the generalized model of multi-path fading channels, the algorithm can also be introduced into measurement of other networks.

In this paper, we use an 802.11n compliant, programmable platform to study channel measurement and prediction in mobile 802.11n networks. Our research shows that the existing PDR-RSS model can't capture the channel quality in 802.11n due to the static model and single measurement input. To this end, we propose a simple and effective online PDR-RSS modeling framework, a dynamic model that explicitly utilizes the real-time PDR and RSS jointly. The online framework derives a set of configurations with certain performance guaranteeing, which overcomes the channel quality capturing problem in static PDR-RSS models. Finally, we develop a rate adaption scheme, GradedR, based on online PDR-RSS modeling framework for mobile 802.11n. The experimental results from experiments in our testbeds indicate that GradedR can significantly improve the throughput under a wide range of configurations.

附录 A 接收信号强度本地均值估计

A.1 统计区间长度

$R_{p_r^2}(\tau)$ it can be derived from (**??**) and (**??**) by approximation[11] as follows:

$$R_{p_r^2}(\tau) = 4\sigma^2 \left[J_0^2\left(\frac{2\pi}{\lambda}\tau\right) + 2KJ_0\left(\frac{2\pi}{\lambda}\tau\right)\cos\left(\frac{2\pi}{\lambda}\eta\tau\right)\right] \tag{A–1}$$

where $J_0(\cdot)$ is the zero-order Bessel function, and $\eta = \cos\theta_0$. Then $\sigma_{\hat{s}}^2$ can be calculated by substituting (A–1) into (**??**).

$$\begin{aligned}\sigma_{\hat{s}}^2 =& \frac{4\sigma^2}{L}\int_0^{2L}\frac{2L-\tau}{2L}[J_0^2(\frac{2\pi}{\lambda}\tau) + 2KJ_0(\frac{2\pi}{\lambda}\tau)\cos(\frac{2\pi}{\lambda}\eta\tau)]d\tau \\ =& \frac{\hat{s}^2(2L-\lambda)\lambda}{2(1+K)^2L^2}\int_0^{\frac{2L}{\lambda}}[J_0^2(2\pi\rho) + 2KJ_0(2\pi\rho)\cos(2\pi\eta)]\rho d\rho\end{aligned} \tag{A–2}$$

where $\rho = \tau/\lambda$ is the intermediate valuable and $\sigma_{\hat{s}}^2 \to 0$ as $2L/\lambda \to \infty$. $\hat{s}$ can be considered as Gaussian distributed when $2L$ is large enough. Then $\sigma_{\hat{s}}^2$ can be represented by the simple form as follows:

$$\sigma_{\hat{s}}^2 = \frac{2(n-1)}{n^2(1+K)^2}\int_0^n g(K;\rho)d\rho \tag{A–3}$$

where $n := 2L/\lambda$ represents the relationship between statistical intervals $2L$ and wireless prorogation wavelength λ, $g(K;\rho) := [J_0^2(2\pi\rho) + 2KJ_0(2\pi\rho)\cos(2\pi\eta)]\rho$ is the intermediate function. Then the estimation error can be calculated as follows:

$$\begin{aligned}
P_e := & 10\log_{10}\left(\frac{\hat{s}+\sigma_{\hat{s}}}{\hat{s}-\sigma_{\hat{s}}}\right) \\
= & 10\log_{10}\left(\frac{n(1+K)+\sqrt{2(1+n)\int\limits_0^n g(K;\rho)d\rho}}{n(1+K)-\sqrt{2(1+n)\int\limits_0^n g(K;\rho)d\rho}}\right) \\
= & 10\log_{10}\left(\frac{\frac{2\sigma^2+\nu^2}{2\sigma^2}n+\sqrt{2(1+n)\int\limits_0^n g\left(\frac{\nu^2}{2\sigma^2};\rho\right)d\rho}}{\frac{2\sigma^2+\nu^2}{2\sigma^2}n-\sqrt{2(1+n)\int\limits_0^n g\left(\frac{\nu^2}{2\sigma^2};\rho\right)d\rho}}\right)
\end{aligned} \tag{A–4}$$

A.2 采样点数目

根据莱斯分布的特性，z_i^2 可以表示为 $z_i^2 = x_i^2 + y_i^2$，其中 $x_i \sim N(\nu\cos\eta, \sigma^2)$ 和 $y_i \sim N(\nu\sin\eta, \sigma^2)$ 为统计独立的正态随机变量，η 为任一实数。令 $x_{0i} = x_i/\sigma$, then $x_{0i} \sim N(\nu\sin\eta, 1)$ and its sum subject to the non-central χ^2 distribution, that is $\sum_{i=1}^N x_{0i}^2 \sim \chi_N^2(\nu^2\cos^2\eta)$. For $E[\chi_n^2(\lambda)] = n+\lambda$ and $D[\chi_n^2(\lambda)] = 2n+4\lambda$, the mean value and variance of $\sum_{i=1}^N x_i^2$ can be calculated by:

$$\begin{aligned}
E\left[\sum_{i=1}^N x_i^2\right] &= \sigma^2 E\left[\sum_{i=1}^N x_{0i}^2\right] \\
&= \sigma^2 E\left[\chi_N^2(\nu^2\cos^2\eta)\right] \\
&= \sigma^2\left(N+\nu^2\cos^2\eta\right)
\end{aligned} \tag{A–5a}$$

$$\begin{aligned}
D\left[\sum_{i=1}^N x_i^2\right] &= \sigma^4 D\left[\sum_{i=1}^N x_{0i}^2\right] \\
&= \sigma^4 D\left[\chi_N^2(\nu^2\cos^2\eta)\right] \\
&= \sigma^4\left(2N+4\nu^2\cos^2\eta\right)
\end{aligned} \tag{A–5b}$$

and $E[\sum_{i=1}^N y_i^2] = \sigma^2(N+\nu^2\sin^2\eta)$, $D[\sum_{i=1}^N y_i^2] = \sigma^4(2N+4\nu^2\sin^2\eta)$ can also be calculated in the same way. Then the expectation of r^2 and its variance can be calculated by:

$$
\begin{aligned}
\bar{r^2} &= E\left[\frac{1}{N}\sum_{i=1}^{N} z_i^2\right] \\
&= \frac{1}{N}E\left[\sum_{i=1}^{N}(x_i^2+y_i^2)\right] \\
&= \frac{\sigma^2}{N}\left(N+\nu^2\cos^2\eta+N+\nu^2\sin^2\eta\right) \\
&= \frac{\sigma^2}{N}\left(2N+\nu^2\right)
\end{aligned} \tag{A–6a}
$$

$$
\begin{aligned}
\sigma_{\bar{r^2}}^2 &= D\left[\frac{1}{N}\sum_{i=1}^{N} z_i^2\right] \\
&= \frac{1}{N^2}D\left[\sum_{i=1}^{N}\left(x_i^2+y_i^2\right)\right] \\
&= \frac{\sigma^4}{N^2}\left(2N+4\nu^2\cos^2\eta+2N+4\nu^2\sin^2\eta\right) \\
&= \frac{\sigma^4}{N^2}\left(4N+4\nu^2\right)
\end{aligned} \tag{A–6b}
$$

Then the estimation error can be calculated as follows:

$$
\begin{aligned}
Q_e &= 10\log_{10}\left(\frac{\bar{r^2}+\sigma_{\bar{r^2}}}{\bar{r^2}}\right) \\
&= 10\log_{10}\left(\frac{\frac{\sigma^2}{N}\left(2N+\nu^2\right)+\frac{2\sigma^2}{N}\sqrt{N+\nu^2}}{\frac{\sigma^2}{N}(2N+\nu^2)}\right) \\
&= 10\log_{10}\left(\frac{2N+\nu^2+2\sqrt{N+\nu^2}}{2N+\nu^2}\right)
\end{aligned} \tag{A–7}
$$

参考文献

[1] Lee W. Estimate of local average power of a mobile radio signal[J]. IEEE Transactions on Vehicular Technology, 1985, 34(1):22–27.

[2] de la Vega D, Lopez S, Matias J, et al. Generalization of the Lee Method for the Analysis of the Signal Variability[J]. IEEE Transactions on Vehicular Technology, 2009, 58(2):506 –516.

[3] Bjornson E, Ottersten B. A Framework for Training-Based Estimation in Arbitrarily Correlated Rician MIMO Channels With Rician Disturbance[J]. IEEE Transactions on Signal Processing, 2010, 58(3):1807 –1820.

[4] Sijbers J, Den Dekker A, Scheunders P, et al. Maximum-likelihood estimation of Rician distribution parameters[J]. IEEE Transactions on Medical Imaging, 1998, 17(3):357–361.

[5] Marzetta T. EM algorithm for estimating the parameters of a multivariate complex Rician density for polarimetric SAR[C]//International Conference on Acoustics, Speech, and Signal Processing, 1995. .[S.l.]: [s.n.] , 1995, 5:3651–3654.

[6] Sarkar T, Ji Z, Kim K, et al. A survey of various propagation models for mobile communication[J]. Antennas and Propagation Magazine, IEEE, 2003, 45(3):51–82.

[7] Hata M. Empirical formula for propagation loss in land mobile radio services[J]. IEEE Transactions on Vehicular Technology, 1980, 29(3):317–325.

[8] Medeisis A, Kajackas A. On the use of the universal Okumura-Hata propagation prediction model in rural areas[C]//IEEE 51st Vehicular Technology Conference Proceedings, 2000. .[S.l.]: [s.n.] , 2000, 3:1815–1818.

[9] Gudmundson M. Correlation model for shadow fading in mobile radio systems[J]. Electronics letters, 1991, 27(23):2145–2146.

[10] Tepedelenlioğlu C, Abdi A, Giannakis G, et al. Estimation of Doppler spread and signal strength in mobile communications with applications to handoff and adaptive transmission[J]. Wireless Communications and Mobile Computing, 2001, 1(2):221–242.

[11] Austin M, Stuber G. Velocity adaptive handoff algorithms for microcellular systems[J]. IEEE Transactions on Vehicular Technology, 1994, 43(3):549–561.

[12] Aja-Fernández S, Niethammer M, Kubicki M, et al. Restoration of DWI data using a Rician LMMSE estimator[J]. IEEE Transactions on Medical Imaging, 2008, 27(10):1389–1403.

[13] Akhoondzadeh-Asl L, Noori N. Modification and Tuning of the Universal Okumura-Hata Model for Radio Wave Propagation Predictions[C]//Asia-Pacific Microwave Conference, 2007. .[S.l.]: [s.n.] , 2007:1 –4.

[14] Andersen J, Rappaport T, Yoshida S. Propagation measurements and models for wireless communications channels[J]. Communications Magazine, IEEE, 1995, 33(1):42–49.

[15] Baldini G, Nai Fovino I, Masera M, et al. An early warning system for detecting GSM-R wireless interference in the high-speed railway infrastructure[J]. International Journal of Critical Infrastructure Protection, 2010. http://www.sciencedirect.com/science/article/pii/S1874548210000430.

[16] DeVore M, Lanterman A, O Sullivan J. ATR performance of a Rician model for SAR images[C]//PROCEEDINGS-SPIE THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING. .[S.l.]: [s.n.] , 2000:34–47.

[17] Goldsmith A, Greenstein L, Foschini G. Error statistics of real-time power measurements in cellular channels with multipath and shadowing[J]. IEEE Transactions on Vehicular Technology, 1994, 43(3):439–446.

[18] Gopal L, Singh A, Shanmugam V. Power Estimation in Mobile Communication Systems[J]. Computer and Information Science, 2009, 1(3):P88.

[19] Itoh K, Watanabe S, Shih J, et al. Performance of handoff algorithm based on distance and RSSI measurements[J]. IEEE Transactions on Vehicular Technology, 2002, 51(6):1460–1468.

[20] Mousa A, Mahmoud H. Channels estimation in OFDM system over rician fading channel based on comb-type pilots arrangement[J]. Signal Processing, IET, 2010, 4(5):598 –602.

[21] Ostlin E, Suzuki H, Zepernick H J. Evaluation of the Propagation Model Recommendation ITU-R P.1546 for Mobile Services in Rural Australia[J]. IEEE Transactions on Vehicular Technology, 2008, 57(1):38 –51.

[22] Saleh A, Valenzuela R. A statistical model for indoor multipath propagation[J]. IEEE Journal on Selected Areas in Communications, 1987, 5(2):128–137.

[23] Zhang N, Holtzman J. Analysis of handoff algorithms using both absolute and relative measurements[J]. IEEE Transactions on Vehicular Technology, 1996, 45(1):174–179.

[24] Zhu H, Yang Q, Kwak K. Performance analysis of fast handoff with mobility prediction[C]//IEEE International Symposium on Communications and Information Technology. .[S.l.]: [s.n.] , 2005 , 1:75–78.

[25] Ahmed N, Ismail U, Keshav S, et al. Online estimation of RF interference[J]. ACM CoNEXT ’08. http://doi.acm.org/10.1145/1544012.1544016.

[26] Balasubramanian A, Mahajan R, Venkataramani A. Augmenting mobile 3G using WiFi[J]. ACM MOBISYS ’10. http://doi.acm.org/10.1145/1814433.1814456.

[27] Boppana R, Su X. On the Effectiveness of Monitoring for Intrusion Detection in Mobile Ad Hoc Networks[J]. IEEE Transactions on Mobile Computing, 2011, 10(8):1162 –1174.

[28] Chen X, Gangwal P, Qiao D. RAM: Rate Adaptation in Mobile Environments[J]. IEEE Transactions on Mobile Computing, 2012, 11(3):464 –477.

[29] Crepaldi R, Lee J, Etkin R, et al. CSI-SF: Estimating wireless channel state using CSI sampling & fusion[J]. IEEE INFOCOM 2012.

[30] Deek L, Garcia-Villegas E, Belding E, et al. The impact of channel bonding on 802.11n network management[J]. ACM CoNEXT '11. http://doi.acm.org/10.1145/2079296.2079307.

[31] Dujovne D, Turletti T, Filali F. A Taxonomy of IEEE 802.11 Wireless Parameters and Open Source Measurement Tools[J]. Communications Surveys Tutorials, IEEE, 2010, 12(2):249 –262.

[32] Fietkau F. Minstrel rate control algorithm for mac80211[缺文献类型标志代码]. http://madwifi-project.org/browser/madwifi/trunk/ath_rate/minstrel.

[33] Floyd S, Handley M, Padhye J, et al. Equation-based congestion control for unicast applications[J]. ACM SIGCOMM '00. http://doi.acm.org/10.1145/347057.347397.

[34] Halperin D, Hu W, Sheth A, et al. Tool Release: Gathering 802.11n Traces with Channel State Information[J]. ACM SIGCOMM CCR. http://ccr.sigcomm.org/online/?q=node/719.

[35] Halperin D, Hu W, Sheth A, et al. Predictable 802.11 packet delivery from wireless channel measurements[J]. ACM SIGCOMM '10. http://doi.acm.org/10.1145/1851275.1851203.

[36] Hiertz G R, Denteneer D, Stibor L, et al. The IEEE 802.11 universe[J]. Comm. Mag., 2010, 48(1):62–70. http://dl.acm.org/citation.cfm?id=1820984.1820997.

[37] Judd G, Wang X, Steenkiste P. Efficient channel-aware rate adaptation in dynamic environments[J]. ACM MOBISYS '08.

[38] KASHYAP A, GANGULY S, DAS S R. A measurement-based approach to modeling link capacity in 802.11-based wireless networks[J]. ACM MOBICOM '07. http://doi.acm.org/10.1145/1287853.1287883.

[39] KIM K, MIN A W, SHIN K G. Sybot: an adaptive and mobile spectrum survey system for wifi networks[J]. ACM MOBICOM '10. http://doi.acm.org/10.1145/1859995.1860029.

[40] KIM K, SHIN K G. On accurate measurement of link quality in multi-hop wireless mesh networks[C]//MobiCom '06. New York, NY, USA: ACM, 2006:38–49, http://doi.acm.org/10.1145/1161089.1161095.

[41] KIM W, KHAN O, TRUONG K, et al. An experimental evaluation of rate adaptation for multi-antenna systems[J]. IEEE INFOCOM 2009.

[42] KOLAR V, RAZAK S, MÄHÖNEN P, et al. Link quality analysis and measurement in wireless mesh networks[J]. Ad Hoc Netw., 2011, 9(8):1430–1447. http://dx.doi.org/10.1016/j.adhoc.2011.03.005.

[43] LENDERS V, MARTONOSI M. Repeatable and Realistic Experimentation in Mobile Wireless Networks[J]. IEEE Transactions on Mobile Computing, 2009, 8:1718–1728.

[44] LIU S, XING G, ZHANG H, et al. Passive interference measurement in Wireless Sensor Networks[J]. IEEE ICNP '10.

[45] NIST/SEMATECH. e-Handbook of Statistical Methods[缺文献类型标志代码]. http://www.itl.nist.gov/div898/handbook/.

[46] PEFKIANAKIS I, HU Y, WONG S, et al. MIMO rate adaptation in 802.11n wireless networks[J]. ACM MOBICOM '10. http://doi.acm.org/10.1145/1859995.1860025.

[47] PELECHRINIS K, SALONIDIS T, LUNDGREN H, et al. Experimental characterization of 802.11n link quality at high rates[C]//WiNTECH '10. New York, NY, USA: ACM, 2010:39–46, http://doi.acm.org/10.1145/1860079.1860087.

[48] Perahia E, Stacey R. Next Generation Wireless LANs: throughput, robustness and reliability in 802.11n[J]. Recherche, 2008, 67:02.

[49] Rayanchu S K, Shrivastava V, Banerjee S, et al. FLUID: improving throughputs in enterprise wireless lans through flexible channelization[J]. ACM MOBICOM'11.

[50] Reis C, Mahajan R, Rodrig M, et al. Measurement-based models of delivery and interference in static wireless networks[J]. ACM SIGCOMM '06. http://doi.acm.org/10.1145/1151659.1159921.

[51] Sevani V, Raman B. SIR based interference modeling for wireless mesh networks: A detailed measurement study[C]//COMSNETS '12. .[S.l.]: [s.n.] , 2012:1 –10.

[52] Smith A. Mobile access 2010[缺文献类型标志代码]. http://www.pewinternet.org/Reports/2010/Mobile-Access-2010.aspx.

[53] Wong M, Gilbert J, Barratt C. Wireless LAN using RSSI and BER parameters for transmission rate adaptation[缺文献类型标志代码].[S.l.]: Google Patents. US Patent 7,369,510.

[54] Zhang J, Tan K, Zhao J, et al. A practical SNR-guided rate adaptation[J]. IEEE INFOCOM 2008.

[55] Zhao J, Govindan R. Understanding packet delivery performance in dense wireless sensor networks[C]//Proceedings of the 1st international conference on Embedded networked sensor systems. 2003. New York, NY, USA: ACM, SenSys '03, http://doi.acm.org/10.1145/958491.958493.

[56] Atheros Linux wireless drivers[缺文献类型标志代码]. http://linuxwireless.org/en/users/Drivers/ath9k.

[57] The MadWifi Project[缺文献类型标志代码]. http://madwifi-project.org.

[58] ARYAFAR E, ANAND N, SALONIDIS T, et al. Design and experimental evaluation of multi-user beamforming in wireless LANs[C]//Proceedings of the sixteenth annual international conference on Mobile computing and networking. 2010. New York, NY, USA: ACM, MobiCom '10, http://doi.acm.org/10.1145/1859995.1860019.

[59] ARYAFAR E, KHOJASTEPOUR M A, SUNDARESAN K, et al. MIDU: enabling MIMO full duplex[C]//Proceedings of the 18th annual international conference on Mobile computing and networking. 2012. New York, NY, USA: ACM, Mobicom '12, http://doi.acm.org/10.1145/2348543.2348576.

[60] BALAN H V, ROGALIN R, MICHALOLIAKOS A, et al. Achieving high data rates in a distributed MIMO system[C]//Proceedings of the 18th annual international conference on Mobile computing and networking. 2012. New York, NY, USA: ACM, Mobicom '12, http://doi.acm.org/10.1145/2348543.2348552.

[61] BALASUBRAMANIAN A, MAHAJAN R, VENKATARAMANI A. Augmenting mobile 3G using WiFi[C]//Proceedings of the 8th international conference on Mobile systems, applications, and services. 2010. New York, NY, USA: ACM, MobiSys '10, http://doi.acm.org/10.1145/1814433.1814456.

[62] BHARTIA A, CHEN Y C, RALLAPALLI S, et al. Harnessing frequency diversity in wi-fi networks[C]//Proceedings of the 17th annual international conference on Mobile computing and networking. 2011. New York, NY, USA: ACM, MobiCom '11, http://doi.acm.org/10.1145/2030613.2030642.

[63] CHAI E, LEE J, LEE S J, et al. Building efficient spectrum-agile devices for dummies[C]//Proceedings of the 18th annual international conference on Mobile computing and networking. 2012. New York, NY, USA: ACM, Mobicom '12, http://doi.acm.org/10.1145/2348543.2348564.

[64] CHOI J I, JAIN M, SRINIVASAN K, et al. Achieving single channel, full duplex wireless communication[C]//Proceedings of the sixteenth annual international conference on Mobile computing and networking. 2010. New York, NY, USA: ACM, MobiCom '10, http://doi.acm.org/10.1145/1859995.1859997.

[65] Dogar F R, Steenkiste P, Papagiannaki K. Catnap: exploiting high bandwidth wireless interfaces to save energy for mobile devices[C]//Proceedings of the 8th international conference on Mobile systems, applications, and services. 2010. New York, NY, USA: ACM, MobiSys '10, http://doi.acm.org/10.1145/1814433.1814446.

[66] Dong M, Zhong L. Self-constructive high-rate system energy modeling for battery-powered mobile systems[C]//Proceedings of the 9th international conference on Mobile systems, applications, and services. 2011. New York, NY, USA: ACM, MobiSys '11, http://doi.acm.org/10.1145/1999995.2000027.

[67] Falaki H, Mahajan R, Kandula S, et al. Diversity in smartphone usage[C]//Proceedings of the 8th international conference on Mobile systems, applications, and services. 2010. New York, NY, USA: ACM, MobiSys '10, http://doi.acm.org/10.1145/1814433.1814453.

[68] Gao P X, Curtis A R, Wong B, et al. It's not easy being green[C]//Proceedings of the ACM SIGCOMM 2012 conference on Applications, technologies, architectures, and protocols for computer communication. 2012. New York, NY, USA: ACM, SIGCOMM '12, http://doi.acm.org/10.1145/2342356.2342398.

[69] Gollakota S, Adib F, Katabi D, et al. Clearing the RF smog: making 802.11n robust to cross-technology interference[C]//Proceedings of the ACM SIGCOMM 2011 conference. 2011. New York, NY, USA: ACM, SIGCOMM '11, http://doi.acm.org/10.1145/2018436.2018456.

[70] Goma E, Canini M, Lopez Toledo A, et al. Insomnia in the access: or how to curb access network related energy consumption[C]//Proceedings of the ACM SIGCOMM 2011 conference. 2011. New York, NY, USA: ACM, SIGCOMM '11, http://doi.acm.org/10.1145/2018436.2018475.

[71] Gudipati A, Katti S. Strider: automatic rate adaptation and collision handling[C]//Proceedings of the ACM SIGCOMM 2011 conference. 2011. New

York, NY, USA: ACM, SIGCOMM ’11, http://doi.acm.org/10.1145/2018436.2018455.

[72] HALPERIN D, HU W, SHETH A, et al. Predictable 802.11 packet delivery from wireless channel measurements[C]//Proceedings of the ACM SIGCOMM 2010 conference. 2010. New York, NY, USA: ACM, SIGCOMM ’10, http://doi.acm.org/10.1145/1851182.1851203.

[73] HAN H, LIU Y, SHEN G, et al. DozyAP: power-efficient Wi-Fi tethering[C]//Proceedings of the 10th international conference on Mobile systems, applications, and services. 2012. New York, NY, USA: ACM, MobiSys ’12, http://doi.acm.org/10.1145/2307636.2307675.

[74] HONG S S, MEHLMAN J, KATTI S. Picasso: flexible RF and spectrum slicing[C]//Proceedings of the ACM SIGCOMM 2012 conference on Applications, technologies, architectures, and protocols for computer communication. 2012. New York, NY, USA: ACM, SIGCOMM ’12, http://doi.acm.org/10.1145/2342356.2342362.

[75] HUANG J, QIAN F, GERBER A, et al. A close examination of performance and power characteristics of 4G LTE networks[C]//Proceedings of the 10th international conference on Mobile systems, applications, and services. 2012. New York, NY, USA: ACM, MobiSys ’12, http://doi.acm.org/10.1145/2307636.2307658.

[76] HUANG J, XU Q, TIWANA B, et al. Anatomizing application performance differences on smartphones[C]//Proceedings of the 8th international conference on Mobile systems, applications, and services. 2010. New York, NY, USA: ACM, MobiSys ’10, http://doi.acm.org/10.1145/1814433.1814452.

[77] JAIN M, CHOI J I, KIM T, et al. Practical, real-time, full duplex wireless[C]//Proceedings of the 17th annual international conference on Mobile computing and networking. 2011. New York, NY, USA: ACM, MobiCom ’11, http://doi.acm.org/10.1145/2030613.2030647.

[78] Keralapura R, Nucci A, Zhang Z L, et al. Profiling users in a 3g network using hourglass co-clustering[C]//Proceedings of the sixteenth annual international conference on Mobile computing and networking. 2010. New York, NY, USA: ACM, MobiCom '10, http://doi.acm.org/10.1145/1859995.1860034.

[79] Kim K H, Min A W, Shin K G. Sybot: an adaptive and mobile spectrum survey system for wifi networks[C]//Proceedings of the sixteenth annual international conference on Mobile computing and networking. 2010. New York, NY, USA: ACM, MobiCom '10, http://doi.acm.org/10.1145/1859995.1860029.

[80] Kjæ rgaard M B, Bhattacharya S, Blunck H, et al. Energy-efficient trajectory tracking for mobile devices[C]//Proceedings of the 9th international conference on Mobile systems, applications, and services. 2011. New York, NY, USA: ACM, MobiSys '11, http://doi.acm.org/10.1145/1999995.2000025.

[81] Li C Y, Peng C, Lu S, et al. Energy-based rate adaptation for 802.11n[C]//Proceedings of the 18th annual international conference on Mobile computing and networking. 2012. New York, NY, USA: ACM, Mobicom '12, http://doi.acm.org/10.1145/2348543.2348585.

[82] Lin K, Kansal A, Lymberopoulos D, et al. Energy-accuracy trade-off for continuous mobile device location[C]//Proceedings of the 8th international conference on Mobile systems, applications, and services. 2010. New York, NY, USA: ACM, MobiSys '10, http://doi.acm.org/10.1145/1814433.1814462.

[83] Lin K C J, Gollakota S, Katabi D. Random access heterogeneous MIMO networks[C]//Proceedings of the ACM SIGCOMM 2011 conference. 2011. New York, NY, USA: ACM, SIGCOMM '11, http://doi.acm.org/10.1145/2018436.2018454.

[84] Ma Y, Banerjee S. A smart pre-classifier to reduce power consumption of T-CAMs for multi-dimensional packet classification[C]//Proceedings of the ACM SIGCOMM 2012 conference on Applications, technologies, architectures, and

protocols for computer communication. 2012. New York, NY, USA: ACM, SIGCOMM '12, http://doi.acm.org/10.1145/2342356.2342428.

[85] Magistretti E, Chintalapudi K K, Radunovic B, et al. WiFi-Nano: reclaiming WiFi efficiency through 800 ns slots[C]//Proceedings of the 17th annual international conference on Mobile computing and networking. 2011. New York, NY, USA: ACM, MobiCom '11, http://doi.acm.org/10.1145/2030613.2030619.

[86] Magistretti E, Gurewitz O, Knightly E. Inferring and mitigating a link's hindering transmissions in managed 802.11 wireless networks[C]//Proceedings of the sixteenth annual international conference on Mobile computing and networking. 2010. New York, NY, USA: ACM, MobiCom '10, http://doi.acm.org/10.1145/1859995.1860030.

[87] Manweiler J, Roy Choudhury R. Avoiding the rush hours: WiFi energy management via traffic isolation[C]//Proceedings of the 9th international conference on Mobile systems, applications, and services. 2011. New York, NY, USA: ACM, MobiSys '11, http://doi.acm.org/10.1145/1999995.2000020.

[88] Mittal R, Kansal A, Chandra R. Empowering developers to estimate app energy consumption[C]//Proceedings of the 18th annual international conference on Mobile computing and networking. 2012. New York, NY, USA: ACM, Mobicom '12, http://doi.acm.org/10.1145/2348543.2348583.

[89] Nath S. ACE: exploiting correlation for energy-efficient and continuous context sensing[C]//Proceedings of the 10th international conference on Mobile systems, applications, and services. 2012. New York, NY, USA: ACM, MobiSys '12, http://doi.acm.org/10.1145/2307636.2307640.

[90] Nguyen N P, Dinh T N, Tokala S, et al. Overlapping communities in dynamic networks: their detection and mobile applications[C]//Proceedings of the 17th annual international conference on Mobile computing and networking. 2011. New York, NY, USA: ACM, MobiCom '11, http://doi.acm.org/10.1145/2030613.2030624.

[91] Paek J, Kim J, Govindan R. Energy-efficient rate-adaptive GPS-based positioning for smartphones[C]//Proceedings of the 8th international conference on Mobile systems, applications, and services. 2010. New York, NY, USA: ACM, MobiSys '10, http://doi.acm.org/10.1145/1814433.1814463.

[92] Paek J, Kim K H, Singh J P, et al. Energy-efficient positioning for smartphones using Cell-ID sequence matching[C]//Proceedings of the 9th international conference on Mobile systems, applications, and services. 2011. New York, NY, USA: ACM, MobiSys '11, http://doi.acm.org/10.1145/1999995.2000024.

[93] Pathak A, Jindal A, Hu Y C, et al. What is keeping my phone awake?: characterizing and detecting no-sleep energy bugs in smartphone apps[C]//Proceedings of the 10th international conference on Mobile systems, applications, and services. 2012. New York, NY, USA: ACM, MobiSys '12, http://doi.acm.org/10.1145/2307636.2307661.

[94] Pefkianakis I, Hu Y, Wong S H, et al. MIMO rate adaptation in 802.11n wireless networks[C]//Proceedings of the sixteenth annual international conference on Mobile computing and networking. 2010. New York, NY, USA: ACM, MobiCom '10, http://doi.acm.org/10.1145/1859995.1860025.

[95] Peng C, Lee S B, Lu S, et al. Traffic-driven power saving in operational 3G cellular networks[C]//Proceedings of the 17th annual international conference on Mobile computing and networking. 2011. New York, NY, USA: ACM, MobiCom '11, http://doi.acm.org/10.1145/2030613.2030628.

[96] Popa L, Kumar G, Chowdhury M, et al. FairCloud: sharing the network in cloud computing[C]//Proceedings of the ACM SIGCOMM 2012 conference on Applications, technologies, architectures, and protocols for computer communication. 2012. New York, NY, USA: ACM, SIGCOMM '12, http://doi.acm.org/10.1145/2342356.2342396.

[97] Qian F, Wang Z, Gerber A, et al. Profiling resource usage for mobile applications: a cross-layer approach[C]//Proceedings of the 9th international confer-

ence on Mobile systems, applications, and services. 2011. New York, NY, USA: ACM, MobiSys '11, http://doi.acm.org/10.1145/1999995.2000026.

[98] Ra M R, Paek J, Sharma A B, et al. Energy-delay tradeoffs in smartphone applications[C]//Proceedings of the 8th international conference on Mobile systems, applications, and services. 2010. New York, NY, USA: ACM, MobiSys '10, http://doi.acm.org/10.1145/1814433.1814459.

[99] Rahul H S, Kumar S, Katabi D. JMB: scaling wireless capacity with user demands[C]//Proceedings of the ACM SIGCOMM 2012 conference on Applications, technologies, architectures, and protocols for computer communication. 2012. New York, NY, USA: ACM, SIGCOMM '12, http://doi.acm.org/10.1145/2342356.2342401.

[100] Rayanchu S, Shrivastava V, Banerjee S, et al. FLUID: improving throughputs in enterprise wireless lans through flexible channelization[C]//Proceedings of the 17th annual international conference on Mobile computing and networking. 2011. New York, NY, USA: ACM, MobiCom '11, http://doi.acm.org/10.1145/2030613.2030615.

[101] Rozner E, Navda V, Ramjee R, et al. NAPman: network-assisted power management for wifi devices[C]//Proceedings of the 8th international conference on Mobile systems, applications, and services. 2010. New York, NY, USA: ACM, MobiSys '10, http://doi.acm.org/10.1145/1814433.1814445.

[102] Sanadhya S, Sivakumar R, Kim K H, et al. Asymmetric caching: improved network deduplication for mobile devices[C]//Proceedings of the 18th annual international conference on Mobile computing and networking. 2012. New York, NY, USA: ACM, Mobicom '12, http://doi.acm.org/10.1145/2348543.2348565.

[103] Schulman A, Navda V, Ramjee R, et al. Bartendr: a practical approach to energy-aware cellular data scheduling[C]//Proceedings of the sixteenth annual international conference on Mobile computing and networking. 2010.

New York, NY, USA: ACM, MobiCom '10, http://doi.acm.org/10.1145/1859995.1860006.

[104] Shen W L, Tung Y C, Lee K C, et al. Rate adaptation for 802.11 multiuser mimo networks[C]//Proceedings of the 18th annual international conference on Mobile computing and networking. 2012. New York, NY, USA: ACM, Mobicom '12, http://doi.acm.org/10.1145/2348543.2348551.

[105] Shepard C, Yu H, Anand N, et al. Argos: practical many-antenna base stations[C]//Proceedings of the 18th annual international conference on Mobile computing and networking. 2012. New York, NY, USA: ACM, Mobicom '12, http://doi.acm.org/10.1145/2348543.2348553.

[106] Vamanan B, Voskuilen G, Vijaykumar T N. EffiCuts: optimizing packet classification for memory and throughput[C]//Proceedings of the ACM SIGCOMM 2010 conference. 2010. New York, NY, USA: ACM, SIGCOMM '10, http://doi.acm.org/10.1145/1851182.1851208.

[107] Wang J, Hassanieh H, Katabi D, et al. Efficient and reliable low-power backscatter networks[C]//Proceedings of the ACM SIGCOMM 2012 conference on Applications, technologies, architectures, and protocols for computer communication. 2012. New York, NY, USA: ACM, SIGCOMM '12, http://doi.acm.org/10.1145/2342356.2342364.

[108] Wei X, Gomez L, Neamtiu I, et al. ProfileDroid: multi-layer profiling of android applications[C]//Proceedings of the 18th annual international conference on Mobile computing and networking. 2012. New York, NY, USA: ACM, Mobicom '12, http://doi.acm.org/10.1145/2348543.2348563.

[109] Zhang X, Shin K G. E-MiLi: energy-minimizing idle listening in wireless networks[C]//Proceedings of the 17th annual international conference on Mobile computing and networking. 2011. New York, NY, USA: ACM, MobiCom '11, http://doi.acm.org/10.1145/2030613.2030637.

[110] Zhuang Z, Kim K H, Singh J P. Improving energy efficiency of location sensing on smartphones[C]//Proceedings of the 8th international conference on Mobile

systems, applications, and services. 2010. New York, NY, USA: ACM, MobiSys '10, http://doi.acm.org/10.1145/1814433.1814464.

[111] Zohar E, Cidon I, Mokryn O O. The power of prediction: cloud bandwidth and cost reduction[C]//Proceedings of the ACM SIGCOMM 2011 conference. 2011. New York, NY, USA: ACM, SIGCOMM '11, http://doi.acm.org/10.1145/2018436.2018447.

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攻读学位期间发表的学术论文目录

[1] Yongsen Ma, Xiaofeng Mao, Pengyuan Du, Chengnian Long, and Bo Li. Dynamic estimation of local mean power in GSM-R networks[J]. under review of Springer Wireless Networks.

[2] Yongsen Ma, Pengyuan Du, Xiaofeng Mao, and Chengnian Long. On-line and dynamic estimation of Rician fading channels in GSM-R networks[C]. In WCSP’12, October 2012.

[3] Pengyuan Du, Lujin Luo, Yongsen Ma, and Chengnian Long. A dual-antenna based handover scheme for GSM-R network[C]. In WCSP’12, October 2012.

[4] 龙承念，马永森，茅晓峰. 结合 GIS 的 GSM-R 网络通信质量测试系统. 中国，CN102595445A[P]. July 2012.

[5] 龙承念，马永森，茅晓峰. GSM-R 网络接收信号强度动态测试算法. 中国，CN102571238A[P]. July 2012.

[6] 龙承念，马永森，茅晓峰，王英杰，黎凌宇，骆理. GSM-R 网络空中接口在线测试与预警系统. 中国，CN102438270A[P]. May 2012.

[7] 马永森，茅晓峰，龙承念. GSM-R 网络空中接口测试系统 v1.0. 中国，2011SR076399[P]. September 2011.

攻读学位期间参与的项目

[1] 铁道部重点课题“GSM-R 网络通信质量测试技术研究”

[2] 国家自然科学基金“认知无线网络动态频谱拍卖机制与优化算法研究”

[3] 国家自然科学基金“智能电网中需求响应与能量有效协同优化与控制”