Analysis of the Periodic Impulsive Noise Asynchronous with the Mains in Indoor PLC Channels

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***Abstract*—Indoor broadband power-line noise is composed of three main terms: impulsive components, narrowband interferences and background noise. Impulsive components can be classified into three groups according to their behavior with respect to the mains cycle: periodic synchronous with the mains, periodic asynchronous with the mains and aperiodic. Periodic asynchronous terms are the most interesting ones because they have significant spectral components in the band used by broadband power-line communication systems. This paper presents a detailed analysis of this noise component in the frequency band up to 25MHz. By means of a methodology that combines both frequency and time domain techniques, repetition rates and pulse waveforms are obtained even in scenarios in which the remaining noise terms have significant level.**

***Index Terms*—Periodic impulsive noise, broadband, power-line communications (PLC).**

I. Introduction

In the last years, a considerable research effort has been carried out in broadband PLC. As a result, there is a good understanding of the channel response characteristics [1], [2], and appropriate models for obtaining representative frequency responses have been proposed [3], [4], [5]. However, there are few works dealing with power-line noise characterization and modeling [2], [6], [7], [8], [9]. The widely accepted classification given in [7] distinguishes the following terms:

1) *Impulsive noise*. It comprises different components that can be also classified according to:
   a) *Periodic impulsive noise synchronous with the mains*. It is a cyclostationary noise, synchronous with the mains and with a frequency of 50 Hz/100 Hz in Europe. It is commonly originated by silicon controlled rectifiers (SCR) in power-supplies.
   b) *Periodic impulsive noise asynchronous with the mains*. It has been traditionally considered to be formed by periodic impulses with rates between 50 kHz and 200 kHz. However, repetition rates outside this range have been found in the measurements accomplished in this work. Moreover, in addition to these high repetition frequencies, this noise type also exhibits a lower periodicity, equal to the mains one. Hence, it can be also categorized as a cyclostationary noise.
   c) *Asynchronous impulsive noise*. It has a sporadic nature, mainly due to transients caused by the connection and disconnection of electrical devices.
2) *Narrowband interferences*. They are mostly formed by sinusoidal or modulated signals coupled via radiation. Their level usually varies with daytime.
3) *Background noise*. It encompasses the rest of noise types not included in the previous categories. It can be assumed to be cyclostationary.

The analysis of the impulsive components performed up to now has been mainly accomplished in the time-domain by means of a digital oscilloscope triggered by a peak detector output. The stored data is employed to compute statistics of the interarrival time, pulse width and pulse amplitude [7], [8]. However, this procedure does not take into account the different characteristics of the three constituent components of this noise term, e.g. it mixes periodic and aperiodic impulses. Moreover, in the periodic noise type, it does not distinguish between the synchronous and the asynchronous terms, which have quite diverse characteristics: periodic synchronous components use to have much higher amplitude and width than periodic asynchronous ones but, on the other hand, the latter have much higher repetition rates. In addition, the presence of the remaining noise terms in the captured data biases the estimation of the pulse width and amplitude. Hence, statistics computed in this way are of little use for the development of realistic noise models.

This paper presents an analysis of the periodic asynchronous impulsive noise performed over more than 50 noise registers measured in three scenarios (laboratories and offices of a university building, an apartment and a detached house). To this end, a novel methodology that combines time domain and frequency domain techniques is firstly proposed in

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section II. Representative examples of pulse waveforms and repetition rates, along with a summary of the main characteristics of the registered components, are provided in section III. Finally, conclusions are given in section IV.

II. Measurement Methodology

The measurement setup consists of a PC with a 12 bits data acquisition card (DAC). It has a configurable dynamic range and an input impedance of 50 Ω. The DAC is plugged to the power network outlets through a coupling circuit that acts as a passband filter and as a balun that extracts differential mode signal. The measured bandwidth extends up to 25 MHz. The captured data is real-time transfered to the PC, allowing recording lengths equivalent to hundreds of mains cycles.

The performed analysis combines time-domain and frequency-domain techniques. It starts by computing a high resolution spectral analysis based on periodogram averaging. Because of the cyclostationary nature of most noise terms, this averaging is performed in a cyclic way. Let's denote by T_o the mains period and by T_s the sampling period, which is selected to be a submultiple of T_o. The output signal from the coupling circuit, $x(n)$, is registered during the time of C mains cycles. Each mains cycle, c, whose nominal length is $N_C = T_o/T_s$ samples, and whose equivalent time jitter is $\tau(c)$ samples, is also divided into L intervals with $N_L = \left\lfloor \frac{T_o}{T_s L} \right\rfloor$ samples. Hence, the captured signal during the ℓth interval of the cth cycle can be written as

$$x_{c,\ell}(n) = x(n + cN_c + \sum_{i=0}^{c} \tau(i) + \ell N_L), \quad (1)$$

with $0 \leq \ell \leq L-1$ and $0 \leq n \leq N_L - 1$. The corresponding periodogram is then computed according to

$$P_c(\ell,k) = \frac{1}{UN_L} \left| \sum_{n=0}^{N_L-1} w(n) x_{c,\ell}(n) e^{-j\frac{2\pi}{N_L}kn} \right|^2, \quad (2)$$

where $w(n)$ is a Hanning window of N_L samples and U is the normalization factor that removes the estimation bias [10]. An estimate of the time and frequency sampled version of the noise instantaneous PSD can then be obtained by performing a synchronized averaging of the periodograms in (2)

$$\widehat{S}_N(\ell,k) = \widehat{S}_N(t,f)\Big|_{t=\ell T_s N_L, f=\frac{k}{T_s N_L}} = \frac{1}{C} \sum_{c=0}^{C-1} P_c(\ell,k), \quad (3)$$

where $0 \leq \ell \leq L-1$, $0 \leq k \leq N_L - 1$, $C = 234$ and $N_L = 2^{16}$, leading to a time and frequency resolution of approximately 1.3 ms and 3 kHz, respectively.

Periodic asynchronous noise components take the form of short duration impulse trains that always appear at the same intervals of the mains cycle. Repetition rates found in this work range from approximately 12 kHz up to 217 kHz. Since the frequency resolution of the spectral analysis is about 3 kHz, these noise terms manifest in the instantaneous PSD as very narrow peaks. Hence, the following procedure is employed to determine the repetition rates and pulse waveforms of the components that are present in a given noise register:

1) *Estimate the instantaneous PSD of the registered noise*. An estimate of the noise instantaneous PSD, $\widehat{S}_N(\ell,k)$, is obtained according to (3).
2) *For each time interval, ℓ, do:*

2.1) *Determine all the spectral peaks in $\widehat{S}_N(\ell,k)$*. It is assumed that $\widehat{S}_N(\ell,k)$ has an spectral peak in $k = k_0$ when $\widehat{S}_N(\ell,k_0)$ is two times greater than the median of $\widehat{S}_N(\ell,k)$ in the band $k_0 - 10 \leq k \leq k_0 + 10$. The output of this phase is an spectral mask, $SP_\ell(k)$, where $SP_\ell(k_0) = 1$ if $\widehat{S}_N(\ell,k)$ has an spectral peak in $k = k_0$, and zero otherwise.

2.2) *Obtain a coarse estimate of the repetition rate of each periodic asynchronous noise term.* A coarse estimate of the repetition rate corresponding to the ith noise component, $\widehat{R}_i^c$, is obtained by locating equally spaced maximums in the autocorrelation of $SP_\ell(k)$.
However, some of the $\widehat{R}_i^c$ obtained with this procedure do not correspond to periodic asynchronous noise terms. The reason is that some of the interferences existing in PLC are composed by a set of equally spaced narrowband spectral components, which also lead to equally spaced maximums in the autocorrelation of $SP_\ell(k)$. Nevertheless, these terms are easily discarded because their spectral peaks are not located in harmonically related frequencies, i.e. denoting by f_j the frequencies of these narrowband spectral peaks, with $j = 0, 1, ...$, it happens that $f_j - f_{j-1} = f_{j+1} - f_j$ but there is no f_0 that satisfies $f_j = pf_0$, for $j = 0, 1, ...$ and $p \in \mathbb{N}^+$.

2.3) *Obtain a fine estimate of the repetition rates*. Let's denote by R_i the actual repetition rate of the periodic asynchronous component under analysis. Although R_i is generally a non-integer value, due to the limited resolution of the spectral analysis, the spectral peaks of this noise term are located at $k \in K_i$ with $K_i = \{0, [R_i], [2R_i], ...\}$, where $[x]$ stands for the closest integer to x. Hence, in the absence of other noise components, $\sum_k SP_\ell(k)$ is maximized when $k \in K_i$. Accordingly, fine estimates of the repetition rates, $\widehat{R}_i^f$, are computed as

$$\widehat{R}_i^f = \arg\max_R \left\{ \sum_{k \in K_i} SP_\ell(k) \right\}, \qquad (4)$$

where $K_i = \{0, [R], [2R], ...\}$ and R is assigned values in a small interval around $\widehat{R}_i^c$.

In practice, the set of frequency samples in K_i must be restricted to the subband where the studied noise component has a significant number of spectral peaks, which can be generally determined by a simple observation of $SP_\ell(k)$. This is done to avoid capturing spectral peaks that do not correspond to the noise term under analysis, which does not occupy all the considered band (0-25 MHz), but to narrowband interferences, some of them located at $[nR_i]$, with $n \in \mathbb{N}^+$.

2.4) *Determine the spectral peaks corresponding to each periodic asynchronous impulsive noise component*. According to the values of $\widehat{R}_i^f$ estimated in 2.3), the spectral peaks corresponding to the ith noise component should be ideally located at $k \in K_i$, with $K_i = \left\{0, \left[\widehat{R}_i^f\right], \left[2\widehat{R}_i^f\right], ...\right\}$. However, due to the limited resolution of the accomplished spectral analysis, values of $k \in K_i - 1$ and $k \in K_i + 1$ do also correspond to the same spectral peak. Thus, the spectral mask corresponding to the ith periodic noise component of the ℓ interval, $M_\ell^i(k)$, is obtained as

$$M_\ell^i(k) = \left\{ \begin{array}{ll} 1 & k \in \{K_i - 1, K_i, K_i + 1\} \\ 0 & elsewhere \end{array} \right. . \qquad (5)$$

2.5) *Obtain the pulse waveform*. The pulse waveform corresponding to the ith noise component of the ℓth interval is obtained as

$$p_i(n) = \text{IDFT}\left\{M_\ell^i(k)\text{DFT}\left\{x_{c,\ell}(n)\right\}\right\}, \qquad (6)$$

where DFT$\{\cdot\}$ and IDFT$\{\cdot\}$ denote the N_L-point Discrete Fourier Transform and Inverse DFT, respectively.

III. Measurements Results

The presented procedure allows to retrieve pulse waveforms with such low amplitude that would be undetectable with the traditional measurement procedure based on a digital oscilloscope triggered by a peak detector. To illustrate this situation, Fig. 1(a) depicts the noise registered in an apartment during one mains cycle. It exhibits two noise components synchronous with the mains. The first one is an impulsive term, with impulses located around 2.55 ms and 12.55ms. The second one appears right before the impulses and lasts for about 3 ms. As the zoomed region displayed in Fig. 1(b) reveals, it is a high-amplitude narrowband interference that unveils the periodic asynchronous impulsive component. However, the estimated PSD for this interval, shown in Fig. 1(c), clearly highlights the presence of the impulsive term. The proposed methodology detects a noise component with a repetition rate of 70 kHz. Fig. 2 depicts its pulse waveform, $p(t)$, and ESD (Energy Spectral Density) defined as

$$ESD(f) = 20\log_{10}\left(|P(f)|\right) \ \ \text{(dBV)}, \qquad (7)$$

where $P(f)$ is the Fourier transform of $p(t)$.

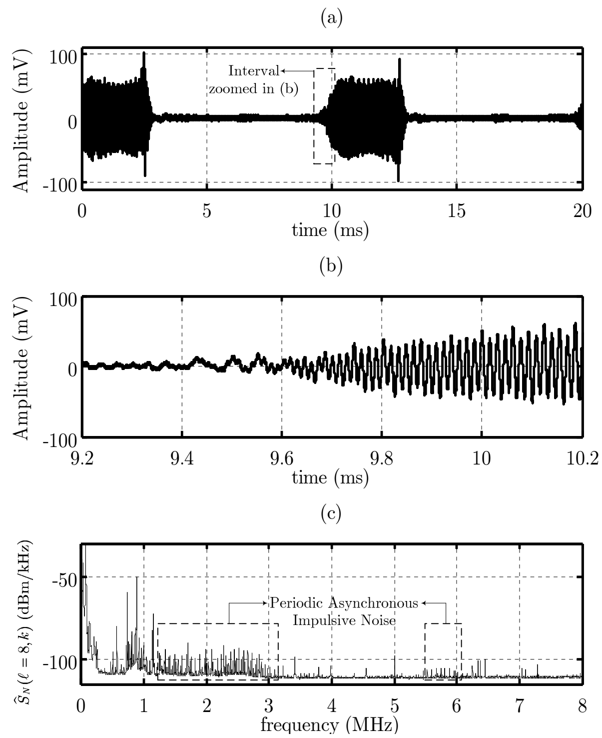

Figure 1. (a) Time-domain plot of the noise registered during a mains cycle; (b) detail of the noise depicted in (a); (c) estimated PSD of an 1.3 ms interval.

The presented method is able to obtain all the periodic asynchronous noise components that are present in a given noise register, even when their spectral components occupy the same frequency band. Fig. 3 depicts the estimated PSD of the noise captured in a university laboratory. The three noise terms have been highlighted with the dashed boxes. As seen, noise terms (a) and (b) partially overlap in frequency. Fig. 4(a) to (c) show their corresponding pulse waveforms. Their repetition rates are 26.4 kHz, 105.7 kHz and 48.8 kHz, respectively.

Fig. 5 shows an example of a periodic asynchronous impulsive noise with high frequency components. Fig. 5(a) depicts the time-domain waveform, which is composed of a higher amplitude and a low amplitude pulse, with approximate durations of 1 μs and 0.5 μs, that re-

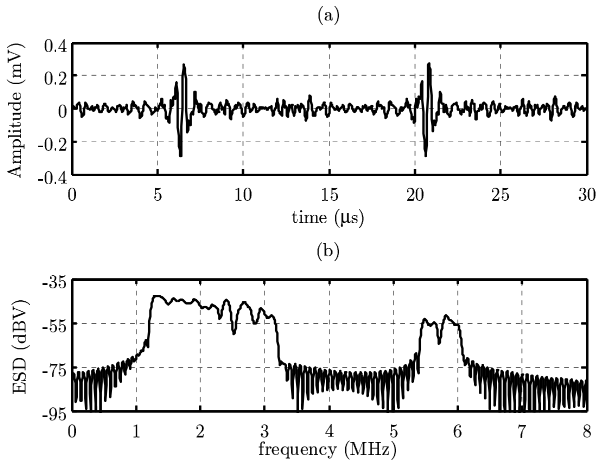

Figure 2. (a) Pulse waveform of the periodic asynchronous noise term shown in Fig. 1(c); (b) ESD of the pulse in (a).

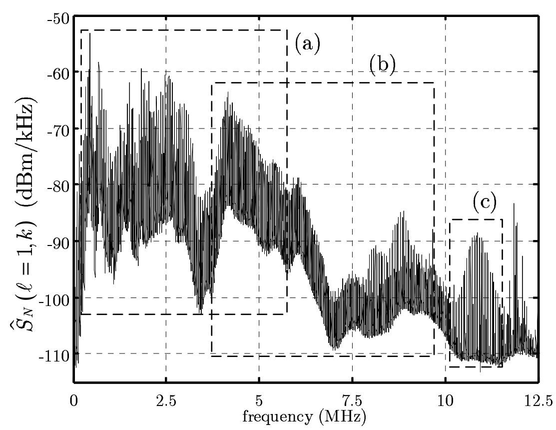

Figure 3. Estimated PSD of the noise registered in a university laboratory.

peat with 90.1 kHz. Fig. 5(b) shows the corresponding ESD.

Periodic asynchronous impulse terms do usually appear only in certain intervals of the mains cycle. These intervals can be determined by correlating the noise register with the pulse waveform obtained with the aforementioned procedure. In some cases, the noise record must be bandpass filtered previous to the correlation in order to eliminate high-amplitude synchronous narrowband interferences. A common appearance pattern is composed of two impulse trains symmetrically located within the mains cycle, both at the vicinity of the zero crossings or around the maximum and the minimum. An example is depicted in Fig. 6(a), where the normalized value of the correlation during a mains cycle is shown. Some periodic asynchronous noise components are present nearly during the whole mains cycle but with different amplitudes, as shown in Fig. 6(b) and (c).

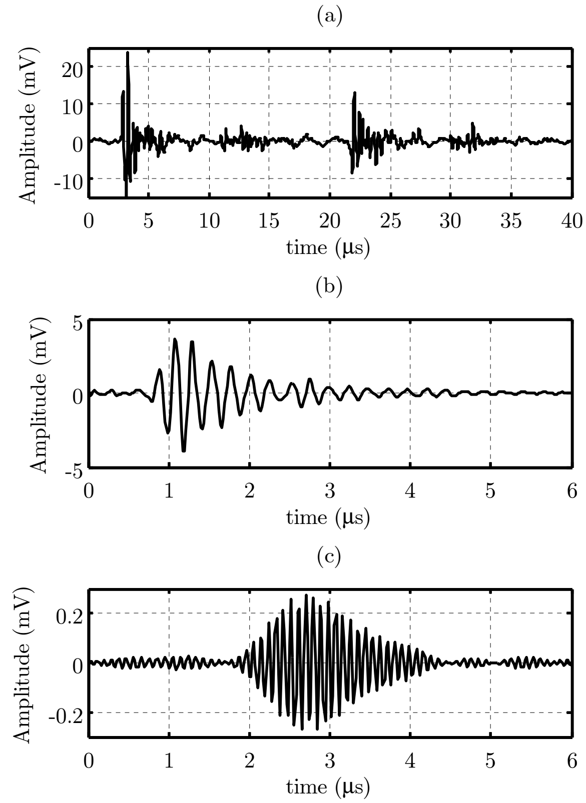

Figure 4. Pulse waveforms corresponding to the noise terms shown in Fig. 3.

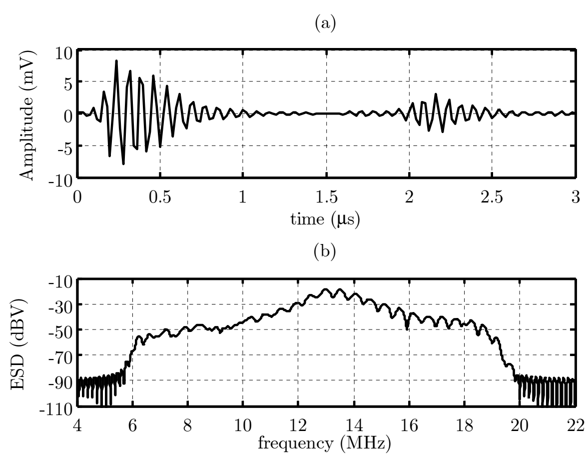

Figure 5. (a) Pulse waveform of a periodic asynchronous impulsive noise with high frequency components; (b) ESD of the pulse in (a).

According to the accomplished measurements, the number periodic impulsive noise terms asynchronous with the mains varies from three (or more) in highly disturbed scenarios like the university laboratories, to one or even none in the apartment. Table I summarizes the main characteristics of the measured components.

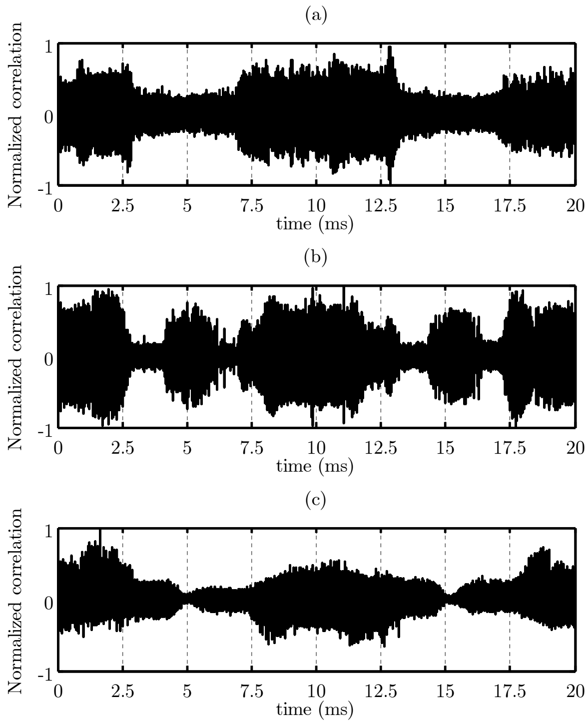

Figure 6. Appearance patterns of different periodic impulsive noise terms asynchronous with the mains.

Table I
SUMMARY OF THE PERIODIC ASYNCHRONOUS IMPULSIVE NOISE CHARACTERISTICS

Parameter	**Value**
Number of different components in a mains cycle	one or none in weakly disturbed scenarios and more than 3 in highly disturbed ones
Appearance pattern	present all the time, 2 states (on/off) per mains cycle, 4 states (on/off) per mains cycle & others
Duration	typically less than 1.5 μs, occasionally up to 10 μs
Amplitude	typically less than 4 mV, occasionally up to 40 mV
Repetition rates	12.6 kHz, 15.6 kHz, 26.3 kHz, 48.9 kHz, 56.5 kHz, 59.1 kHz, 70 kHz, 90.1kHz and 217.2kHz
Central frequency	from 2 MHz up to 13 MHz
Bandwidth	from 2 MHz up to 9 MHz

IV. CONCLUSION

This paper has presented a detailed analysis of the periodic impulsive noise asynchronous with the mains that exists in the indoor broadband power-line scenario. The employed methodology combines time-domain techniques with a high resolution spectral analysis based on periodogram averaging that captures the cyclostationary nature of this noise term. The study relies on a measurement campaign performed over more than 50 noise registers in three different scenarios in the frequency band up to 25 MHz.

It has been shown that this noise component exhibits a synchronous behavior with the mains. Repetition rates from 12.6 kHz up to 217.2 kHz have been measured. Examples of pulse waveforms and their corresponding energy spectral densities, along with a summary of its main characteristics, have been given.

ACKNOWLEDGMENT

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REFERENCES

[1] H. Philipps, “Performance measurements of power-line channels at high frequencies,” in *Proceedings of the International Symposium on Power Line Communications and its Applications (ISPLC)*, 1998, pp. 229–237.

[2] F. J. Cañete, J. A. Cortés, L. Díez, and J. T. Entrambasaguas, “Analysis of the cyclic short-term variation of indoor power line channels,” *IEEE Journal on Selected Areas on Communications*, vol. 24, no. 7, pp. 1327–1338, July 2006.

[3] F. J. Cañete, L. Díez, J. A. Cortés, and J. T. Entrambasaguas, “Broadband modelling of indoor power-line channels,” *IEEE Transactions on Consumer Electronics*, pp. 175–183, Feb 2002.

[4] T. Esmailian, F. R. Kschischang, and P. G. Gulak, “In-building power lines as high-speed communication channels: channel characterization and a test channel ensemble,” *International Journal of Communications*, vol. 16, pp. 381–400, June 2003.

[5] S. Galli and T. C. Banwell, “A deterministic frequency-domain model for the indoor power line transfer function,” *IEEE Journal on Selected Areas on Communications*, vol. 24, no. 7, pp. 1304–1316, July 2006.

[6] Y. Hirayama, H. Okada, T. Yamazato, and M. Katayama, “Noise analysis on wide-band plc with high sampling rate and long observation time,” in *Proceedings of the International Symposium on Power Line Communications and its Applications (ISPLC)*, 2003, pp. 142–147.

[7] M. Zimmermann and K. Dostert, “Analysis and modeling of impulsive noise in broad-band powerline communications,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 44, no. 1, pp. 249–258, February 2002.

[8] V. Degardin, M. Lienard, A. Zeddam, F. Gauthier, and P. Degauque, “Classification and characterization of impulsive noise on indoor power line used for data communications,” *IEEE Transactions on Consumer Electronics*, vol. 48, no. 4, pp. 913–918, November 2002.

[9] D. Liu, E. Flint, B. Gaucher, and Y. Kwark, “Wide band AC power line characterization,” *IEEE Transactions on Consumer Electronics*, vol. 45, no. 4, pp. 1087–1097, November 1999.

[10] A. Oppenheim, R. Schafer, and J. Buck, *Discrete-time Signal Processing*. Prentice Hall, 1999.