Equations for optimizing RFID links involving targets in 1-d motion.

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***Abstract*— This work discusses the RFID reading contexts of targets in 1-d motion. The problem to be solved is a function of the final reading rate that can be optimized. A set of variables constitutes the parameter group extracted from a simplified Friis model taking into account the presence of obstacles such as ground and its electromagnetic properties. The speed influence of targets in motion (containing RFID tags) is also discussed since it directly affects the final number of readings for the reader-tag pair, given an input power.**

Keywords*— *signal propagation, Radio Frequency Identification, electromagnetic propagation.

I. INTRODUCTION

The idea of using RFID UHF tags in vehicle tracking and tolling is just a subset of all possible application of the RFID technology wave of the past 30 years [1,2,3]. In particular, RFID tags operating in the ISM band for region II (902-928MHz) [4] have been extensively used in a wide variety of static applications [5,6,7] – as in targets in motion [8,9,10, 11]. Vehicles constitute classical cases of dynamical RF interaction in which attributes of radiating structures, i. e., gain, antenna impedance matching, radiation lobe coverage among others, are extremely critical. Depending on the vehicle speed and other tag features, besides energy requirements, the interaction between the tag and the electromagnetic field of the RFID reader becomes a bottleneck. Several interesting problems appear in UHF tags [12,13], depending on limits such as chip energy budget [12]. Laws limit the reader output power [14,15]. Engineers should exercise creativity in order to design antenna structures [16] to maximize reading rates, taking into account environmental challenges, which, on the tag side, include tag-windshield interaction and presence of parasitic components in the chip-antenna port.

A relevant issue in the tag-reader coupling is the effective interaction zone between these elements. The reading zone may be defined as the region where a given number of successful readings takes place [17] and coincides with the region where sufficient power is available. In this sense, the reading zone is a statistical concept since at, its border, signal suffers fast degradation and is influenced by background noise. Although such limitations, the use of RSSI (received signal strength indication) [18,19,20] characterizes the reading zone [21]. In tolling applications [22,23] vehicles of different types must be correctly identified and charged. Also other physical barriers set limits for RFID interaction time, including possible access identification databases and account numbers. Furthermore, the presence of more than one vehicle in the reading zone gives rise to side readings that must be minimized somehow by limiting the horizontal radiation lobes. This is not to circumvent collisions [24,25], but to reduce the probability of vehicle-tag association error in the event of ill vehicle-vehicle separation and queuing problems.

Maxwell equations may be integrated [26] to calculate the reading zone, but for higher carrier frequencies, reflective and absorbing boundaries may harden the task by increasing the number of calculation cells and field nodes [27]. A "quick and easy" way of calculating propagation amplitudes may thus be advantageous mainly if the problem can be set up as a function of a geometry as close as possible to the real situation. In the case of RFID involving a vehicle tag and a reader, the geometry is limited to a two dimensional degree of freedom involving the presence of the most important reflecting boundaries, as the ground for a given tag-reader polarization configuration. Friis model has been extensively used [28,29,30,31] as a simplified approach including reflection boundaries and permits an experimental comparison with sensibility power thresholds both for reader and tag. Wireless communications [32,33] have long used Friis model mainly to treat problems where the involved distances are much larger than the problem wavelength. In order to model RFID link using this equation, a sufficiently accurate model of the reader and tag antenna geometries must be known. This article reviews the many of geometrical details involved in calculating the reading zone (for both the tag and the reader) including reflection terms for tags attached to one objects in one dimensional motion and then discuss how this model can be used to optimize the RFID reading rate.

A. 1-d Problem geometry

Coordinate system and angle measures must be established to apply Friis equation and obtain the received power at a tag antenna in 1-d motion over the pavement. Figure 1 depicts the problem geometry including reflection. The tag antenna is represented by the rectangular structure t, moving horizontally with speed v, while the reader is represented by r. The y position of t and r is h_t and h_r above the pavement, respectively. The radiation pattern of each structure is oriented according to the normal vectors, $\mathbf{n}_t$ and $\mathbf{n}_r$ respectively, so that the emitted signal at the reader is attenuated by a gain function depending on the angle θ_r (between $\mathbf{n}$ and $\mathbf{n}_r$), while the received signal at t will be modulated by the radiation gain function depending on θ_t (between $\mathbf{n}$ and $\mathbf{n}_t$). The reflection contribution is generated by a mirror image of r denoted r', located h_r below the pavement, so that the reflected signal at t depends on $\theta_{t'}$ (between $\mathbf{n'}$ and $\mathbf{n}_t$).

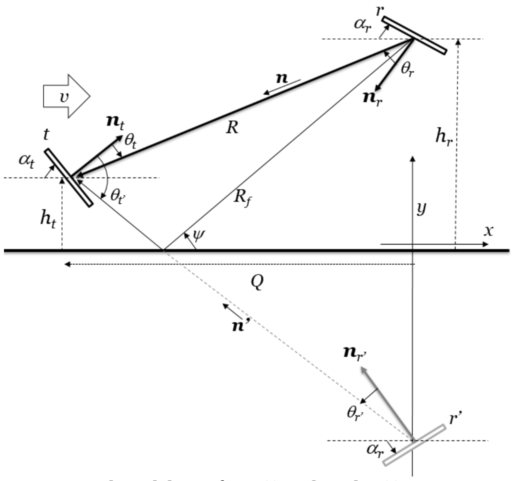

Figure 1 Geometrical modeling of tag (t) and reader (r) interaction including reflection due to a mirror reader at r'

Reflected signal intensity depends on the position angle $\theta_{r'}$ between **n'** and $\mathbf{n}_{r'}$. The orientation angles $\mathbf{n}_t$ and $\mathbf{n}_r$ may be written down in terms of α_t and α_r, which are antenna orientation angles in relation to the motion line or t. In general, α_t coincides with widescreen angle while α_r is the reader installation angle in relation to the horizontal line. The tag antenna will located at Q measured along the x-axis and having as origin the reader foot. Hence, Q is negative. The tag power at Q is

$$P_t(Q) = P_0\left(\frac{\lambda}{2\pi}\right)^2\left|\frac{\sqrt{G_r(\theta_r)}\sqrt{G_t(\theta_t)}}{R} + \Gamma\frac{\sqrt{G'_r(\theta'_r)}\sqrt{G'_t(\theta'_t)}}{R'}e^{-j\Delta\phi}\right|^2 \tag{1}$$

where P_0 is the reader output power, λ is the wavelength, $G_r(\theta_r)$ is the reader vertical gain depending on θ_r and $G_t(\theta_t)$ the tag vertical gain depending on θ_r. This equation may be rewritten in terms of more fundamental geometric elements, since, for fixed α_t and α_r, auxiliary angles are given as function of Q. We note that

$$R = \sqrt{Q^2 + (h_r - h_t)^2}, \tag{2}$$

$$R' = \sqrt{Q^2 + (h_r + h_t)^2}, \tag{3}$$

$$\Delta\phi = \frac{2\pi}{\lambda}(R - R'), \tag{4}$$

$$\Gamma = \frac{\sin\psi - \sqrt{\varepsilon - (\cos\psi)^2}}{\sin\psi + \sqrt{\varepsilon - (\cos\psi)^2}}, \tag{5}$$

with R the length of the direct ray, R' the corresponding length of the reflected ray, $\Delta\phi$ the phase difference between line of sight and reflected rays and $\Gamma = \varepsilon r - j\sigma/\omega\varepsilon 0$ a complex reflection coefficient for the horizontal polarization as a function of the pavement electric properties, dielectric constant, ε , conductivity, σ and angle of incidence ψ as shown in Figure 1. The geometrical functions for Eqs. (1-5) are

$$\theta_r = \cos^{-1}[\mathbf{n}_r(\alpha_r)\cdot\mathbf{n}],\ \theta_t = \cos^{-1}[-\mathbf{n}_t(\alpha_t)\cdot\mathbf{n}],$$
$$\theta'_r = \cos^{-1}[\mathbf{n}'_r(\alpha_r)\cdot\mathbf{n}'],\ \ \theta'_t = \cos^{-1}[-\mathbf{n}_t(\alpha_t)\cdot\mathbf{n}'], \tag{6}$$

$$\psi = \tan^{-1}\left(\frac{h_t + h_r}{|Q|}\right), \tag{7}$$

$$\mathbf{n} = \frac{1}{\sqrt{Q^2 + (h_r - h_t)^2}}\begin{pmatrix} Q \\ -(h_r - h_t)\end{pmatrix}, \tag{8}$$

$$\mathbf{n}' = \frac{1}{\sqrt{Q^2 + (h_r + h_t)^2}}\begin{pmatrix} Q \\ h_r + h_t\end{pmatrix}, \tag{9}$$

$$\mathbf{n}_r(\alpha_r) = \frac{-1}{\sqrt{1 + (\tan\alpha_r)^2}}\begin{pmatrix}\tan\alpha_r \\ 1\end{pmatrix}, \tag{10}$$

$$\mathbf{n}'_r(\alpha_r) = \frac{-1}{\sqrt{1 + (\tan\alpha_r)^2}}\begin{pmatrix}\tan\alpha_r \\ -1\end{pmatrix}, \tag{11}$$

$$\mathbf{n}_t(\alpha_t) = \frac{1}{\sqrt{1 + (1/\tan\alpha_t)^2}}\begin{pmatrix} 1 \\ 1/\tan\alpha_t\end{pmatrix}. \tag{12}$$

The reader received power is again given by Eq. (1) but the new input is

$$P_t(Q)\Theta[P_t(Q) - P_{tag\_lim}]e^{-R_c} \tag{13}$$

that is, P_0 in Eq. (1) is substituted by Eq. (13), with $\Theta(x)$ the Heaviside step function [34]. In Eq. (13), R_c is a reflection factor that accounts for the scattering electromagnetic scattering in the tag structure [35, 36], P_{tag_lim} is a power threshold below which no reading exist. Since the reader sensitivity is limited to values above P_{reader_lim}, another constraint must be imposed according to which

$$P_r(Q)\Theta[P_r(Q) - P_{reade\_lim}]. \tag{14}$$

Figure 2 is an example of angular relationship between the vehicle position Q and the reader and tag direct ray normal angles for h_r = 4.5 m, h_t = 0, α_t =45° and α_r = 30°. Since α_t = 45°, θ_t will be zero for Q = -h_r while the same holds for θ_r , that is, for Q = -h_r tan (α_r).

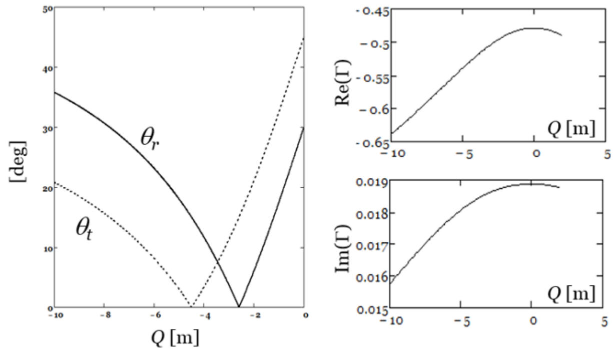

Figure 2 Reader and tag direct ray normal angles (left) as a function of vehicle position Q in meters. Real and Imaginary parts of Γ (Eq. 5) for h_r =5.5 m and h_t = 2m.

Radiation lobes must be calculated in the vertical plane as a function of θ. Gain functions may be expressed in polynomial series

$$D(\theta) = \sum_{n=1}^{M} c_n\theta^n\ , \tag{15}$$

with c_n real coefficients and M setting the series truncation. Therefore

$$G(\theta) = 10^{D(\theta)/10}\ . \tag{16}$$

A practical directivity function is

$$D_Q(\theta) = \left(\frac{4\pi}{N(k)}\right)U_k\left(\theta + \frac{\pi}{2}\right)\Theta(\theta), \tag{17}$$

with $\Theta(x)$ the Heaviside function ,

$$U_k(x) = \sin x^k\ , \tag{18}$$

and

$$N(k) = \int_0^{2\pi}\int_0^{\pi} U_k(\theta)\sin\theta\, d\theta d\varphi. \tag{19}$$

II. Results and Discussions

Previous discussion presented a closed set of equations to determine the 1-d RFID zone that can be calibrated to empirical RSSI values. Power sensibility thresholds can be compared to equivalent values measured in static tests in the lab. As the windshield angle approaches 90º, an interference pattern due to ground reflection becomes evident as shown in Figure 3. The parameters used in this simulation were: α_r = 15º, α_t = 75º and 45º, P_0 = 20dBm, h_r = 5.5m, h_t = 2m, R_c = 6dB, P_{tag_lim} = -30dBm, P_{reader_lim} = -75dB, tag and reader gains are 1.04 dBi and 12.5 dBi respectively.

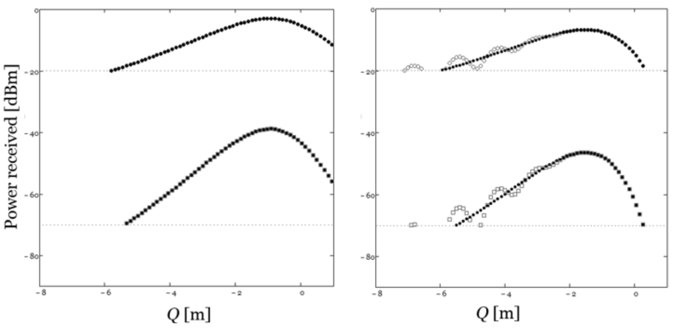

Figure 3 Tag (circles) and reader (squares) received power curves in dBm. Black dots represent the received power without the reflection term. Left plot: windshield angle θ_t=45º. Right plot: windshield angle θ_t=75º. The levels show thresholds for tag and reader sensitivity respectively.

As shown in Figure 3 (right), the resulting reader received power is severely influenced by ground reflection, showing "power oscillations" mainly just after the tag entrance in the reading zone. The power then experiences a maximum whose position is a function of all problem parameters. Such oscillations show that the reading zone is not a simply connected region, and the total number of readings is a sum of many zone pieces, which strongly depend on the tag angle. This phenomenon is particularly strong for θ_t ~ 90º (in the tolling scenario, the case of trucks and buses) and is absent in "face-to-face" reader-tag interactions. Therefore, for a given fixed speed, the total number of readings may show "jumps" as the reader power is changed. Such phenomenon is particularly relevant if tight limits are imposed on the maximum reader power.

A. Optimization problem

It is clear from the presented formalism and discussion that an optimization problem can be set, having a minimum set of parameters {p}. The total number of readings, N, is a function of this set and the tag speed *v*. This number is simply given by the product of the reading density ρ (number of readings per length interval affected by speed and reading rate,η) by the extension of the reading zone L({p}). Readings take place in the interval Δt and, since $v = L/\Delta t$, then $N = L(\{p\})\eta/v$. The reading zone is the "power length", that is, the space region where the reader received power is above P_{reader_lim} as defined by Eq. (14) and (1). Hence, the problem to be solved is to maximize a function L({p}), that is to obtain the optimum set {p*} for a given *v*. This problem may be used to solve a plethora of RFID contexts. The minimum set of parameters involves: the reader and tag position angles as defined in Figure 1, reader and tag gain, reader and tag sensibility thresholds and reader output power. Empirically, the reader position is fixed but its optimum value may be found as a function of: tag position, tag height above ground and tag gain. Conversely, given a fixed reader position, the maximization of N may be used to find the optimal tag position or gain (which gives rise to optimizing tag antenna design). Such are the cases involving vehicle identification, where the tag height from the ground is somewhat restricted to vehicle classes. For example, for cars, h_t is mostly 1.5m, while trucks distances higher than 2 m may be regarded. From a practical approach, it is easy to see that no global solution exist for the problem since it is impossible to fix tag properties, ground height is just one of them. In fact, one typically has an *ensemble* of tag distribution angles representing distinct vehicle populations and the task is to determining an average reader position angle that best serves both groups (in the form of an average value, for example, or distinct reader antennas dedicated to each tag group). Different tag gains will give rise to distinct reading zones. Since the total number of readings is speed dependent, there will be different speed limits for each tag classes (it is easy to see that as $v \to \infty$ N goes to zero). Fixing a maximum allowed speed, the optimization problem may be solved in the context discussed here. To solve the problem, numerical methods such as Steepest Descent [37] are recommended since arbitrary gain functions may be used to represent reader and tag antennas.

The optimization may follow the RFID context as discussed previously and may involve:

1. Fix the target speed (which is a suitable approximation for many tag motion states);
2. Fix a given reader input power. In general, this power must be set to the maximum allowed power;
3. Fix a restricted subset of problem parameters;
4. Optimize the remaining variables and find the optimum set;
5. For the optimum set, release the reader power and find its optimum value given the set {p*} found in the previous steps.

Thus, an iterative approach can be used to find distinct RFID target parameters. In other problems, there will be a minimum N (for example, N =1), that is, a minimum number of RFID readings necessary to provide complete identification. Therefore, the optimization problem may look for the maximum allowed speed *v*, which may not coincide with the traffic (for vehicle identification) allowed speed. Then, steps 1-5 above may search for this speed assuming all other electromagnetic and geometrical parameters are free to change.

III. Conclusions

In this work, we have presented a closed set of equations using Friis propagation formula to solve the optimization problem of 1-d moving tags. In addition, we have discussed a method to find optimal solutions in the RFID link for tags in motion. According to this approach, the identification of targets in motion assumes alignment between tag and reader, but the 1-d tag motion is arbitrary. This model can be used to:

- Obtain accurate limits for the reader power: this is important considering the existence of power regulation limits [14,15];
- Determine intervals for reader installation angles as a function of distinct target populations;
- Determined the influence of target speed in the total number of readings and problem geometry;

- Determine suitable power thresholds for internal tag and reader sensitivities;
- Determine the reading zone extension as a function of a given geometry or maximize the zone for a subset of fixed parameters;
- Calculate the total number of readings for a given target speed;
- Introduce statistical functions, paving the way to a probabilistic treatment of the RFID problem for tags in motion.

Some presented simulations show the importance of considering the effect of ground reflections, which manifests themselves in the form of “power tail oscillations” in the reader power distribution as a function of tag position. Such features result in a close relation for the entire reading zone, which then must be expanded as a sum of many terms. Accordingly, the total number of readings is given by the product of the total reading zone extension and the reading rate, divided by the target speed. Thus, physical, geometrical and electromagnetic variables are interrelated by the presented model in order to provide approximate solutions for a several RFID problem contexts.

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REFERENCES

[1] D. Henrici, *RFID Security and Privacy: Concepts, Protocols and Architectures*, Springer, 2008.

[2] E. C. Jones and C. A. Chung, *RFID in Logistics: a Practical Introduction*, CRC Press, 2008.

[3] J. Landt, "The History of RFID", *IEEE Potentials*, **24**, 4, 2005, pp. 8-11,

[4] M. Golio ed.,*The RF and Microwave Handbook*, CRC Ptess, 2001.

[5] M. Ollivier, "RFID enhances materials handling", *Sensor Review*, **15**, 1, 2005, pp. 36 – 39.

[6] L. B. Ayre, *RFID in Libraries: a step toward interoperability*, volume 48, Number 5, ALA TechSource, 2012.

[7] D. M. Dobkin and T. Wandinger, "A Radio-Oriented Introduction to Radio Frequency Identification", *High Frequency Electronics*, Summit Technical Media, 2005, pp. 46-54.

[8] E.K. Lee, Y. M. Yoo, C. G. Park, M. Kim and M. Gerla, "Installation and evaluation of RFID readers on moving vehicles", *Proceedings of the sith ACM International workshop on Vehicular InterNETworking*, ACM New York, 2009, pp. 99-108.

[9] Q. Jinghui, S. Bo and Y. Qudi, "Study of RFID Antenna for Railway Vehicle Identification", *Proceedings of the 6th International Conference on ITS Telecommunications*, IEEE, 2006, pp. 237-240.

[10] G. Wolfram, B. Gampl and P. Grabriel (Eds.), *The RFID Roadmap: The Next Steps for Europe*, Springer, 2008.

[11] K. Ali and H. Hassanein, "*Passive RFID for Intelligent Transportation Systems*", 6th IEEE Conference on Consumer Communications and Networking, 2009, pp. 1-2.

[12] J. P. Curty, M. Declercq, C. Dehollain and N. Joehl, *Design and Optimizaton of Passive UHF RFID Systems*, Springer, 2007.

[13] V. Chawla, "An overview of passive RFID", *IEEE Communications Magazine*, **45**, 9, 2007, pp. 11-17.

[14] FCC Regulation Part 15. See http://www.fcc.gov/

[15] ANATEL, Resolução 506, 1 de Julho de 2008. http://legislacao.anatel.gov.br/

[16] D. Guha and Y. M. M. Antar (Eds.), "*Microstrip and Printed Antennas - New Trends, Techniques and Applications*”, Wiley, 2011.

[17] Dobkin, D. M. (2012). *The RF in RFID: UHF RFID in Practice*. Newnes.

[18] Heurtefeux, K., & Valois, F. (2012, March). Is RSSI a good choice for localization in Wireless Sensor Network? In *Advanced Information Networking and Applications (AINA), 2012 IEEE 26th International Conference on (pp. 732-739). IEEE.*

[19] Chung, W. Y. (2007, November). Enhanced RSSI-based real-time user location tracking system for indoor and outdoor environments. In *Convergence Information Technology*, 2007. International Conference on (pp. 1213-1218). IEEE.

[20] Jiang, Joe-Air, Cheng-Long Chuang, Chia-Pang Chen, and Tzu-Shiang Lin. "A RSSI-based environmental-adaptive dynamic radiation power management for wireless sensor networks." In *Circuits and Systems*, 2008. APCCAS 2008. IEEE Asia Pacific Conference on, pp. 1046-1049. IEEE, 2008.

[21] Foina, Aislan G., Silvio E. Barbin, and Francisco J. Ramirez. "A new approach for vehicle access control using active RFID tags." In *Microwave and Optoelectronics Conference*, 2007. IMOC 2007. SBMO/IEEE MTT-S International, pp. 90-93. IEEE, 2007.

[22] F. C. Theophilo, "*Highway Tools in Brazil and the Lawfulness Principle*", University of Western Ontario Electronic Thesis and Dissertation Repository, Paper 1267, 2013.

[23] D. Crawford, "Brazil opts for free-flow tolling", *ITS International*, **20**, 2, 2014, pp. 45-46.

[24] Liu, H. C. (2010). The Approaches in Solving Passive RFID Tag Collision Problems. INTECH Open Access Publisher.

[25] L., Han, J., Qi, Y., Wang, C., Liu, Y., Cheng, Y., & Zhong, X. (2010, September). Revisting tag collision problem in RFID systems. In Parallel Processing (ICPP), 2010 39th International Conference on (pp. 178-187). IEEE.

[26] Masuda, T., Miyazaki, Y., & Kashiwagi, Y. (2007). Analysis of electromagnetic wave propagation in out-door active RFID system using FD-TD method.PIERS online, 3(6), 937-939.

[27] Excell, P. S., Tinniswood, A. D., & Haigh-Hutchinson, K. (1998). Parallel computation of large-scale electromagnetic field distributions. *Applied Computational Electromagnetics Society Journal*, 13, 179-187.

[28] H. T. Friis, “A note on a simple transmission formula”, *Proc. IRE*, 1946, pp. 254-256.

[29] Hogg, D. C. (1993). Fun with the Friis free-space transmission formula. *Antennas and Propagation Magazine*, IEEE, 35(4), 33-35.

[30] Friis, H. T., Crawford, A. B., & Hogg, D. C. (1957). A Reflection Theory for Propagation Beyond the Horizon. *Bell System Technical Journal*, 36(3), 627-644.

[31] Shaw, J. A. (2013). Radiometry and the Friis transmission equation. *American Journal of Physics*, 81(1), 33-37.

[32] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed.Singapore: Pearson Education, Inc., 2002

[33] S. Haykin and M. Moher, *Modern Wireless Communications*. Singapore: Pearson Education, Inc., 2002

[34] R. P. Kanwal, "*Generalized Functions - Theory and Applications*", 3rd Edition, Birkhäuser, 2004.

[35] P. V. Nikitin, K. V. S. Rao, "Theory and measurement of backscattering from RFID tags", *IEEE Antennas and Propagation Magazine*, **48**, 6, 2006, pp. 212-218.

[36] P. V. Nikitin, K. V. S. Rao, S. F. Lam, V. Pillai, R. Martinez and H. Heirich, “Power Reflection Coefficient Analysis for Complex Impedances in RFID Tag Design”. *IEEE Transactions on Microwave Theory and Techniques*, **53**, 9, pp. 2721-2725.

[37] Luenberger, D. G. *Introduction to linear and nonlinear programming*. Reading, MA: Addison-Wesley, 1973.