Analysis of an Internet-Inspired EV Charging Network in a Distribution Grid

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***Abstract*—Electric vehicles (EVs) are transforming the modern transportation and energy systems. However, due to increasing battery and charger capacities with long charging times, potential adverse effects on distribution grid will become a crucial problem. Safe and efficient operation of the grid along with a fast, convenient, and fair charging strategy is an important research tackle. In this paper, we analyze the additive increase-multiplicative decrease (AIMD) method used to solve a similar problem occurred in the early days of the Internet and apply it to EV charging using only local measurements. Then, we present a detailed analysis to understand the relationship between distance and charging power in a distribution network to better address the fairness in the proposed AIMD EV charging algorithm.**

I. Introduction

Electric vehicles (EVs) are becoming more popular all across the globe with a variety of benefits such as reduced CO_2 emissions, efficient utilization of battery energy, and lower maintenance requirements. Their mass adoption is finally becoming a mere reality. With a growing EV market, the mass penetration of EVs into the utility grid will result in critical issues such as increased peak loading, increased losses, and voltage imbalance or deviations, and need for additional network reinforcements. Therefore, *advanced and practical* interaction methods between plug-in electric vehicles (PEVs) and the utility grid need to be developed. These methods should satisfy maximum charging rate for each vehicle and preserve charging fairness among them while assuring the grid reliability and distribution power quality.

EV grid integration studies in the literature discusses two broad operations: i) unidirectional charging, and ii) vehicle-to-grid (V2G) power transfer. Algorithms propose grid load leveling, peak shaving, voltage regulation, and reactive power compensation [1]–[3]. Some studies use neural networks taking advantage of the smart grid metering and communication [4]. The developed charging algorithms mostly rely on some sort of centralized information exchange [5]. However, these approaches require centralized server to detect congestion in the network and do not fully address the fairness among users. Alternatively, using local measurements in a decentralized manner, studies propose such a voltage-based feedback controller for EV charging with a preset voltage reference value for all nodes [6], [7].

In literature, among many others, Additive Increase and Multiplicative Decrease (AIMD) algorithm adopted from the Internet congestion control have been proposed for EV charging, where charging power is adjusted in accordance with the congestion status of the distribution grid [8], [9]. This idea was further enhanced by taking power system constraints into account [10]. A distributed AIMD solution using local voltages is discussed in [11], where it suggests that voltage thresholds are obtained from historical voltage data. In [12], an improved decentralized AIMD algorithm is proposed where voltage threshold values are calculated by power flow analysis. A general framework and comparison among different charging strategies are also presented [13], [14].

As presented in the above literature studies, decentralized operation of an EV charging algorithm fundamentally relies on the measured and preset threshold voltage values. This makes it even more important to understand the effects of any system parameters on these values and discover useful relationships among them. In this study, we present a detailed analysis regarding the relationships among distance vs. voltage and power in a simplified distribution grid model which is inspired by an IEEE 37-node model [15]. Then, using the results of this analysis, we propose a method that ensures fairness in an AIMD based charging algorithm. Lastly, we compare it with different charging scenarios and discuss the outcomes of these cases.

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Algorithm 1 Proposed AIMD algorithm.

Input: Charger voltage and current: $V_c(t)$, $I_c(t)$
Output: Charger current command $I_c(t+1)$
  if $V_c(t) > V_{th}(t)$ **then**
    $I_c(t+1) = I_c(t) + \alpha(t)$
  else
    $I_c(t+1) = I_c(t) \times \beta(t)$
  end if

II. AIMD-Based EV Charging Control

A. Baseline AIMD algorithm

In this study, we build from the baseline AIMD algorithm shown in Algorithm 1 for EV charging. This algorithm either increases or decreases the charging current, thus charging power, depending on the measured local node voltage, $V_c(t)$, which can be assumed as an indicator for a congestion/overloading event occurring in the power grid. The amount of increase, which is determined by $\alpha(t)$ coefficient, is done additively whereas that of decrease is a multiplicative factor, $\beta(t)$ as commonly implemented in computer networks [16]. Further, AIMD algorithm is stability proven and can be implemented without instability concerns in a network [17].

Here the threshold value $V_{th}(t)$ is the most crucial to the algorithm as it serves as a congestion indicator. However, voltage level at a certain point on the grid may vary depending not only on the grid structure and distribution line lengths but also on the overall system load at any time. Choosing wrong threshold may cause the violation of fairness among customers as well as ineffective utilization of power. Understanding the relationship among these system parameters and developing insight on how to choose voltage thresholds are essential to ensure fair and effective operation of the AIMD algorithm.

B. Deriving Voltage Thresholds

1) A Simplified Voltage-Distance Relation: We use a single mainline type of distribution system, simplified by considering an IEEE 37-node test feeder [15]. The model is further simplified into a DC circuit (due to resistive behavior of the distribution system) as shown in Fig. 1. Distribution lines are modeled as resistors and loads are modeled as controlled current sources. The parameters are as follows:

- $V_1, V_2, V_3..., V_n$ are the main feeder voltages.
- $V_{i1}, V_{i2}, V_{i3}..., V_{ik}$ are the i_{th} lateral feeder voltages.
- $R_1, R_2, R_3..., R_n$ are distribution lines of the main feeder.

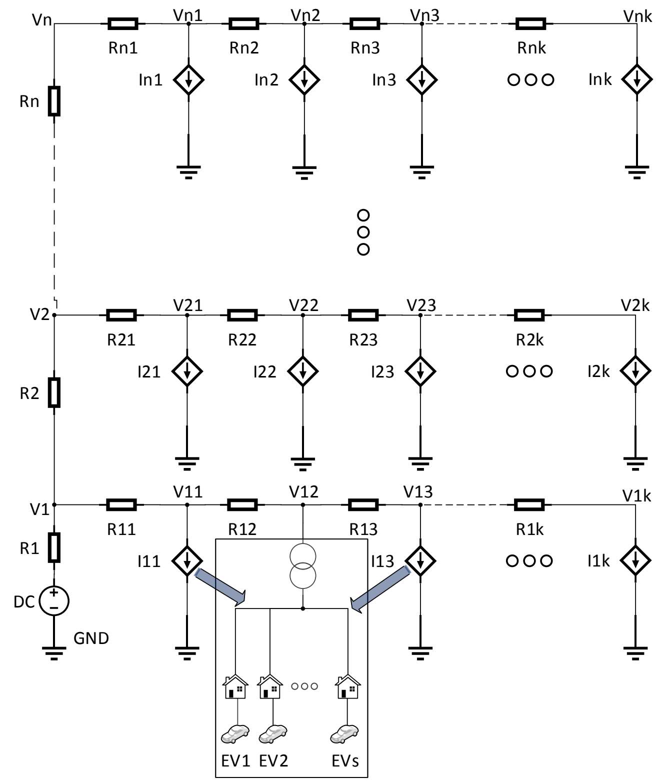

Figure 1: Baseline distribution system model.

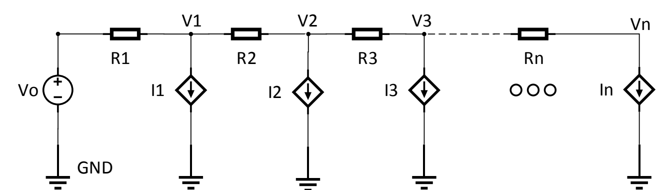

Figure 2: Repeated pattern in the distribution system model.

- $R_{i1}, R_{i2}, R_{i3}..., R_{ik}$ are distribution lines of the i_{th} lateral feeder.
- $I_{i1}, I_{i2}, I_{i3}..., I_{ik}$ are the currents drawn from the i_{th} lateral feeder.

This grid model can be considered as a nested system that repeats itself. The repeated pattern is shown in Fig. 2. To solve this repeated system for node voltages, each node voltage is expressed in terms of other system variables such that i^{th} node voltage can be written as:

$$V_i = V_0 - (I_1 + I_2 + \cdots + I_n)R_1 - (I_2 + \cdots + I_n)R_2 - (I_i + \cdots + I_n)R_i \quad (1)$$

where n is the total number of nodes.

As seen in (1), the voltage of any node in the grid is determined by the distribution line parameters and all the currents drawn at all nodes at any time. This results

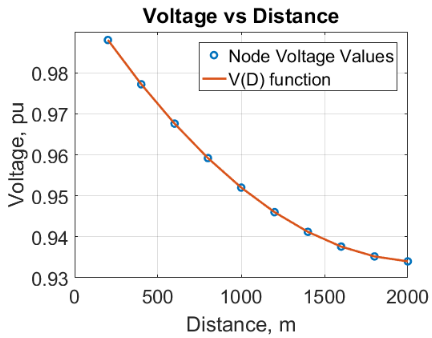

Figure 3: Relationship between voltage and distance.

in a complicated system without a simple analytic equation. However, one can formulate voltage vs. distance relationship when the following assumptions hold true:

- All currents are the same $I_1{=}I_2{=}\,I_3{=}\cdots{=}I_n{=}I$
- All distribution line segment lengths and parameters are the same s.t.: $R_1{=}R_2{=}R_3{=}\cdots = R_n{=}\rho\, L/A$.

where ρ is line resistivity ($\Omega \cdot m$), L is line segment length (m), A is line cross-sectional area (m^2) of the wire. Voltage can, then, be expressed as a function of distance for i^{th} node:

$$V(D) = V_0 - \frac{I\rho}{A}(n+\frac{1}{2})D + \frac{I\rho}{A}\frac{D^2}{2L} \tag{2}$$

where $D = Li$ (i being any node number). Only with the presented assumptions, it was possible to simplify (1) into a quadratic function of a single variable (distance) as presented in (2). The result is shown in Fig. 3. This curve shows that even when simplified, the relationship between voltage and distance is not linear due to the topology of the grid. However, (2) helps us to understand how the voltage signature changes throughout the network when a voltage-based controller is to be used such as an AIMD algorithm.

2) Maximally Fair Voltage Thresholds: After understanding the system voltage dynamics in Fig. 2 using (1), we can calculate the active power P_i absorbed by the i^{th} node as:

$$P_i{=}V_0\, I_i{-}I_i \Big\{(I_1{+}I_2{+}\cdots{+}I_n)R_1{+}(I_2{+}\cdots{+}\, I_n)R_2 + \cdots {+}(I_i+\cdots{+}\, I_n)R_i\Big\} \tag{3}$$

To dedicate the same amount of power P to each node (i.e., to maximize fairness), one has to solve this non-linear system of equations for a specific set of currents. This operation inherently needs a significant computational power and takes a lot of time to complete for large n. A decent and rational simplification can be made by assuming an average current in each power equation which is the same as the corresponding node current. This assumption greatly simplifies the problem, significantly decreases the computation time and holds well enough as long as current values, thus node voltages, are close to one another. This is a safe approximation since, in a typical distribution system, voltages do not deviate so much from its nominal value. This leads to an independent second order equation of single variable for P_i:

$$P_i{=}V_0 I_i - I_i^2\Big\{nR_1{+}(n{-}1)R_2{+}\cdots{+}(n{-}i{+}1)R_i\Big\} \tag{4}$$

Let A_i be the i^{th} element of the vector A, which is the product of the following two matrices:

$$A = \begin{bmatrix} n & 0 & 0 & \cdots & 0 \\ n & n-1 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ n & n-1 & n-2 & \cdots & 1 \end{bmatrix}_{nxn} \times \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{bmatrix}_{nx1} \tag{5}$$

Then, the power for the i^{th} node (4) can rewritten as:

$$P_i = V_0 I_i - I_i^2 A_i \tag{6}$$

For a specific power $P_i = P$, we obtain a simple second order equation that we need to solve for the i^{th} current:

$$-I_i^2 A_i + V_0 I_i - P = 0 \tag{7}$$

For (7) to have real roots, the following must hold:

$$A_i \leq \frac{V_0^2}{4P} \tag{8}$$

As P increases in (8), the right hand side decreases and it gets more likely that the inequality breaks down. Therefore, P has to be restricted. The maximum possible P is determined by the minimum allowable threshold voltage V_{thr} at the last node. From (1), the current that results in this threshold voltage can approximately be found by again assuming an average current that is the same as the corresponding node current:

$$I_n = \frac{V_0 - V_{thr}}{A_n} \tag{9}$$

Then, P is calculated as:

$$P = I_n \cdot V_{thr} \tag{10}$$

and substituted into (7) to solve for current I_i required at each node to distribute the same power P. If these currents are used to solve the system in Fig. 2, then the voltages, currents and power consumed by each node for a 15-node system will be as in Fig. 4. When this solution is expanded for the nested system described in Fig. 1, the lateral feeder voltages and end-node voltages along

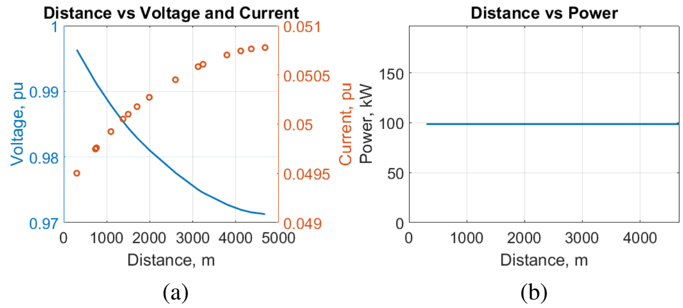

Figure 4: (a) Main feeder voltages and currents wrt distance, (b) Main feeder power wrt distance.

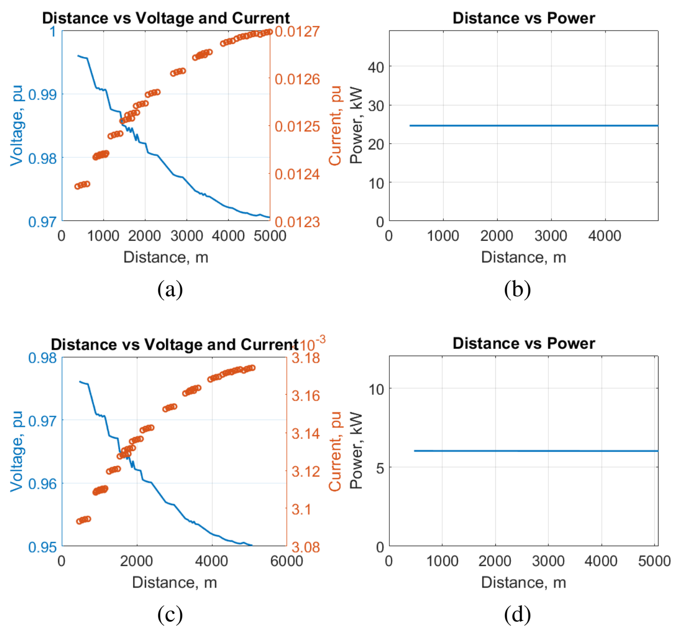

Figure 5: (a) Lateral feeder voltages and currents, (b) lateral feeder power, (c) end-node voltages and currents, and (d) end-node powers.

with the associated powers will be as in Fig. 5. As shown in Figs. 4(b), 5(b), and 5(d), the same amount of power can be allocated to each node regardless of the distance by adjusting the currents. We can conclude that the node voltages resulted from these currents can be used as the voltage thresholds for our AIMD algorithm to maximize fairness between EVs.

III. Simulation Results

To test the ability of the proposed method to determine the voltage thresholds in the AIMD algorithm, we run a simulation case study. The simulation is conducted for the grid model in Fig. 1 with the following parameters:

- Number of main feeder nodes = 15
- Number of lateral feeder nodes = $4 \times 15 = 60$
- Number of end nodes/customers = $4 \times 60 = 240$

Each lateral node has four inner end-nodes which simulates four houses connected to a common pole transformer in a neighborhood. EV model types, battery SOCs, arrival and departure times, and household load consumption are chosen to be the same to clearly see the effects of the distance and how much the proposed method compensates for it to result in a fair sharing of power.

The voltage results for four nodes at increasing distances and power results for all distances are obtained for the following cases and shown in Fig. 6:

- Case 1: Charging without any control
- Case 2: AIMD control with fixed V_{th}
- Case 3: AIMD control with distance-dependant V_{th} using home and EV loads
- Case 4: AIMD control with distance-dependant V_{th} using only EV loads

In Case 1, all the EVs are charged with the maximum possible power, which is the same to all, causing significant voltage drops that increase with the distance to the substation as shown in Fig. 6(a)-(b). In Case 2, the AIMD algorithm with a fixed voltage threshold is implemented at all nodes and this causes an unfair share of the total charging power which decays with the distance as shown in Fig. 6(c)-(d). In Case 3, distance depended voltage thresholds result in a fairer allocation of power, and thus, equal charging durations all across the grid as shown in Fig. 6(e)-(f). Lastly in Case 4 as shown in Fig. 6(g)-(h), we see an improvement in the fair share of the charging powers when the household loads are eliminated during the charging time. This again shows us that any load in the system can contribute to the unpredicted nature of the grid and violate fairness. Note that the oscillation seen in the results are not a sign for instability. Rather, as noted before, AIMD is stability-proven, and the EV chargers oscillate dynamically around their equilibrim point.

IV. Conclusions and Future Work

Voltage vs. distance relationship in a distribution network is highly non-linear due to different node currents and line distances. With the presented method, one can allocate almost same power to all end-nodes under certain assumptions. Voltage levels after allocation of this power can be used as voltage threshold in an AIMD algorithm.

However, the presented voltage threshold derivation methodology requires availability of the complete system information (e.g., the distribution line lengths) at a central location. Thus, as is, it is not a fully decentralized

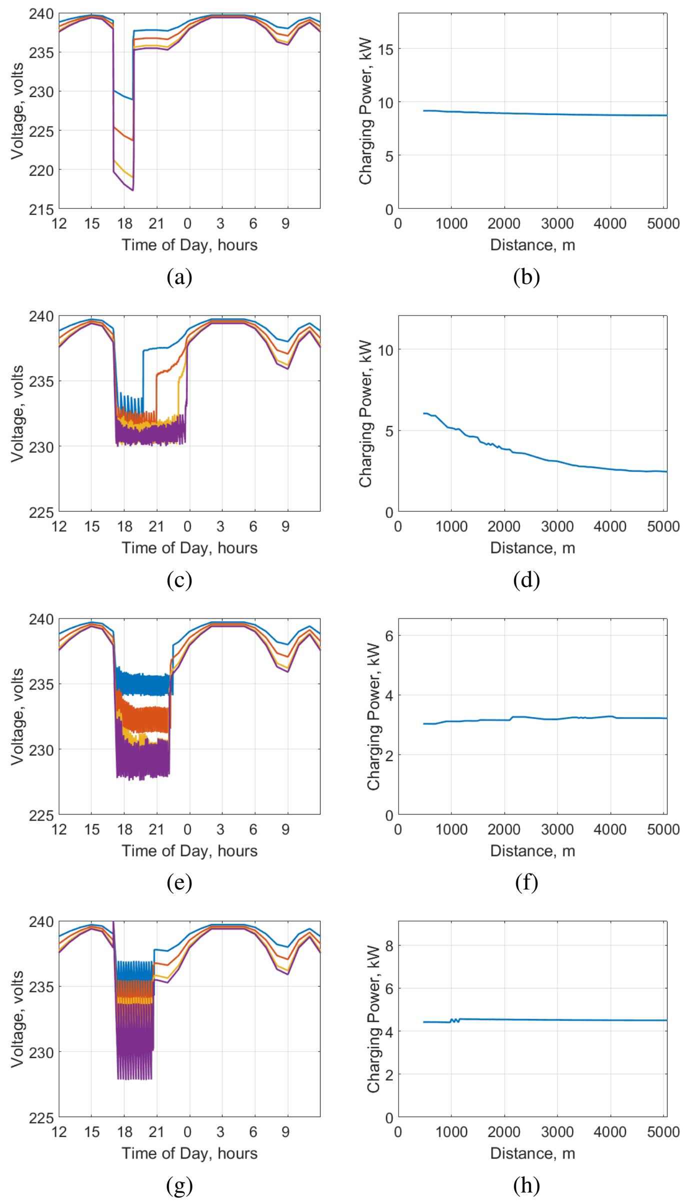

Figure 6: Voltages and charging power of the four selected end-nodes located at different distances to the substation (a)-(b) Case 1, (c)-(d) Case 2, (e)-(f) Case 3, (g)-(h) Case 4

method. Complementary future work will be to develop techniques that can learn the location of a node with respect to the substation using local measurements and their signatures. Further, considering a more generalized system where each node may occasionally provide power (e.g., as a renewable energy source) in addition to using it for EV charging will be studied as well. A smart power management in the light of this work enpowered with a local learning mechanism that applies to any other power consuming device will also be investigated in the future.

References

[1] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, "A controllable local peak-shaving strategy for effective utilization of pev battery capacity for distribution network support," *IEEE Trans. Ind. Appl.*, vol. 51, no. 3, pp. 2030–2037, 2015.

[2] S. Deilami, A. S. Masoum, P. S. Moses, and M. A. Masoum, "Real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve voltage profile," *IEEE Trans. Smart Grid*, vol. 2, no. 3, pp. 456–467, 2011.

[3] M. C. Kisacikoglu, M. Kesler, and L. M. Tolbert, "Single-phase on-board bidirectional PEV charger for V2G reactive power operation," *IEEE Trans. Smart Grid*, vol. 6, no. 2, pp. 767–775, 2015.

[4] S. Morsalin, K. Mahmud, and G. Town, "Electric vehicle charge scheduling using an artificial neural network," in *IEEE Innovative Smart Grid Tech.- Asia*, 2016, pp. 276–280.

[5] M. C. Kisacikoglu, F. Erden, and N. Erdogan, "Distributed control of PEV charging based on energy demand forecast," *IEEE Trans. Ind. Informat.*, vol. PP, no. 99, pp. 1–1, 2017.

[6] A. T. Al-Awami, E. Sortomme, G. M. A. Akhtar, and S. Faddel, "A voltage-based controller for an electric-vehicle charger," *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 4185–4196, 2016.

[7] A. T. Al-Awami and E. Sortomme, "Electric vehicle charging modulation using voltage feedback control," in *IEEE Power Energy Soc. General Meeting*, 2013, pp. 1–5.

[8] S. Studli, E. Crisostomi, R. Middleton, and R. Shorten, "AIMD-like algorithms for charging electric and plug-in hybrid vehicles." IEEE Internat. Electric Vehicle Conf., Mar. 2012, pp. 1–8.

[9] S. Studli, R. H. Khan, R. H. Middleton, and J. Y. Khan, "Performance analysis of an aimd based ev charging algorithm over a wireless network," in *Australasian Universities Power Eng. Conf. (AUPEC)*, 2013, pp. 1–6.

[10] M. Liu and S. McLoone, "Enhanced AIMD-based decentralized residential charging of EVs," *Transactions of the Institute of Measurement and Control*, vol. 37, no. 7, pp. 853–867, 2015.

[11] I. Mareels, T. Alpcan, M. Brazil, J. de Hoog, and D. a. Thomas, "A distributed electric vehicle charging management algorithm using only local measurements," *IEEE Innovative Smart Grid Tech. Conf. (ISGT)*, pp. 1–5, 2014.

[12] M. J. Zangs, P. B. E. Adams, T. Yunusov, W. Holderbaum, and B. A. Potter, "Distributed energy storage control for dynamic load impact mitigation," *Energies*, vol. 9, no. 8, 2016.

[13] M. Liu, P. McNamara, and S. McLoone, "Fair charging strategies for EVs connected to a low-voltage distribution network," in *IEEE Innovative Smart Grid Tech. Conf.–Europe (ISGT)*, 2013.

[14] M. Liu, P. McNamara, R. Shorten, and S. McLoone, "Residential electrical vehicle charging strategies: the good, the bad and the ugly," *J. Modern Power Sources Clean Energy*, vol. 3, no. 2, pp. 190–202, 2015.

[15] A. R. Malekpour and A. Pahwa, "Radial test feeder including primary and secondary distribution network," in *North American Power Symp.*, Oct 2015, pp. 1–9.

[16] D.-M. Chiu and R. Jain, "Analysis of the increase and decrease algorithms for congestion avoidance in computer networks," *Comput. Networks ISDN Syst.*, vol. 17, no. 1, pp. 1 – 14, 1989.

[17] S. H. Low and D. E. Lapsley, "Optimization flow control – I: basic algorithm and convergence," *IEEE/ACM Trans. Netw.*, vol. 7, no. 6, pp. 861–874, Dec 1999.