Physics Letters A 380 (2016) 88–97

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Boolean gates on actin filaments

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ARTICLE INFO

Article history:
Received 9 July 2015
Received in revised form 12 September 2015
Accepted 14 September 2015
Available online 24 September 2015
Communicated by C.R. Doering

Keywords:
Actin
Computation
Logic
Soliton

ABSTRACT

Actin is a globular protein which forms long polar filaments in the eukaryotic cytoskeleton. Actin networks play a key role in cell mechanics and cell motility. They have also been implicated in information transmission and processing, memory and learning in neuronal cells. The actin filaments have been shown to support propagation of voltage pulses. Here we apply a coupled nonlinear transmission line model of actin filaments to study interactions between voltage pulses. To represent digital information we assign a logical TRUTH value to the presence of a voltage pulse in a given location of the actin filament, and FALSE to the pulse's absence, so that information flows along the filament with pulse transmission. When two pulses, representing Boolean values of input variables, interact, then they can facilitate or inhibit further propagation of each other. We explore this phenomenon to construct Boolean logical gates and a one-bit half-adder with interacting voltage pulses. We discuss implications of these findings on cellular process and technological applications.

Actin is a globular structural protein; one of the most highly conserved eukaryotic proteins, ranging from unicellular organisms to plants and animals. Actin plays a key role in cell motility forming actin filaments (microfilaments), which in turn generate parallel bundles that the cell utilises for contractility, in cell division for the creation of the cleavage furrow and in cell motility. Actin has also been correlated with nervous system activity and learning: actin cytoskeleton affects synaptic properties leading to learning, actin and its regulatory proteins are involved in various stages of memory [1–5]. The actin filament networks are key players in modulation of synaptic terminals due to their interactions with ion channels [6] and filtration of noise in synapses [7,8]. By modulating dendritic ion channel activity actin filaments govern neural information processing and facilitate computational abilities of dendritic trees via facilitation of ionic condensation and ion cloud propagation [9].

Previously we proposed a model of actin filaments as two chains of one-dimensional binary-state semi-totalistic automaton arrays to signalling events, and discovered local activity rules that support travelling or stationary localisations [10]. This finite state machine model has been further extended to a quantum cellular automata (QCA) model in [11]. We have shown that quantum actin automata can perform basic operations of Boolean logic, and implemented a binary adder [11], and three valued logic operations [12]. These models were implemented in general algorithmic terms, without describing any specific physical mechanisms that could be used to implement cell excitations and interactions. They also did not employ interactions between propagating localisations in a spirit of collision-based computing [13].

We aim to rectify these omissions and present a model of actin in terms of RLC (resistance, capacitance, inductance) non-linear electrical transmission wires that can implement logical gates via interacting voltage impulses. These models take inspiration from the idea of a CA, but do not fit exactly in its definition, as cells do not possess discrete states, there are no intrinsic time steps, and no rules are defined for state transitions. However, the states can be digitised by defining a suitable threshold, a time step can be defined by convenience and transitions are governed by Kirchhoff's circuit laws so that a deterministic evolution takes place even in absence of explicit transition rules.

Our starting point is the usual model of electrical wires as sequences of circuits composed by resistors, capacitors and inductors. Our model is based on Tuszynski et al. [14] model of actin monomers in terms of electrical components. This latter model was developed in order to explain experimental observations of ionic conductivity along actin filaments [15]. This model exhibits, in a continuous limit, solitons (standing waves and travelling impulses).

The aim of the present work is to use the same equations as in [14] but without invoking the continuous limit approximation

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http://dx.doi.org/10.1016/j.physleta.2015.09.024

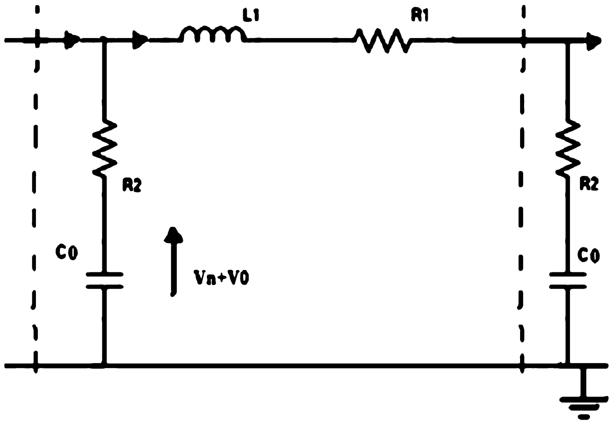

Fig. 1. A circuit diagram for the n-th unit of an actin filament (from [14]).

and to study the behaviour of several types of solutions for tens of monomers. We will show how an excitation moves along the actin filament and how it collides with another excitation coming from elsewhere; we will show that these collisions can be used to implement logical operations. This could provide a physical description of signal propagation and processing in the cellular milieu and also possibly in hybrid bio-nano-technological applications.

1. Actin filaments as nonlinear RLC transmission lines

In this section we recall the basic model that is bused throughout the paper. The underlying mechanism is as follows: we expect a potential difference between the filament core and the ions lying along the filament; a time-dependent current generated by the ions' movement along helical paths, responsible for the inductance L; a resistive component R_1 to these currents, due to viscosity, in series with L; a resistance in parallel to these components, R_2, between the ions and the surface of the filament; and a capacitance C_0. More details can be found in the original paper [14].

Referring to Fig. 1, where an actin monomer unit in a filament is delimited by the dotted lines, we assume that capacitors are nonlinear (see discussion in [16,17] where formulas of electro-

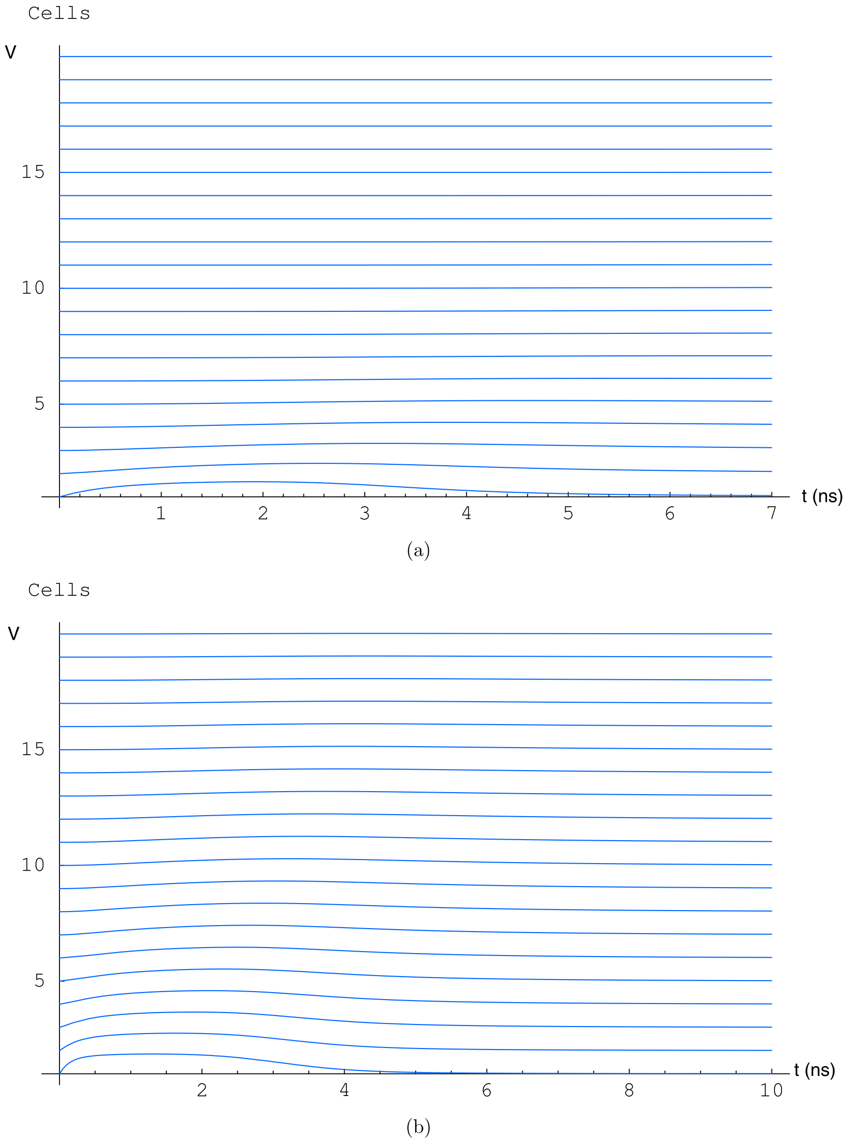

Fig. 2. An input pulse travelling along actin filament: (a) parameters (8), (b) the same parameters but $R_1 = 61.1 \cdot 10^5\ \Omega$. The pictures represent the cell evolutions, each cell voltage is represented by a diagram with time on the horizontal axis and voltage V on the vertical one. The diagrams are tiled vertically with cell 1 at the bottom and cell 20 at the top, with a unitary displacement.