Discrete Simulation of Sound Propagation in the City Based on Cellular Automaton

Eloi Keita, Valéry M. Monthé, Bernard Pottier

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Eloi B. KEITA[1*], Valery MONTHE[3] and Bernard POTTIER[2]

{eloi.keita, valery.monthe, bernard.pottier}@univ-brest.fr

University of Brest, Brest, France

*Corresponding author

Abstract. This paper deals with the problem of sound propagation in urban areas. It begins by investigating the propagation of sound in order to determine and extract the physical parameters that direct this propagation. The formalism of cellular automata (CA) is presented, as well as its use for the specification of physical phenomena, with discrete events, such as sound propagation. The use of cellular automata in a smart city context, to model the propagation of sound is presented. The proposed model takes into account buildings and other city obstacles. A CUDA Implementation of this model is described. This implementation is used to simulate sound propagation on shapefile cards. The proposed model makes it possible to determine the sound power in a given location and the geographic area covered by the sound wave.

Introduction

Our work focuses on sound propagation simulation in urban environment, in a distributed manner. The purpose of this paper is a proposal for modelling and simulation of the propagation of sound waves in urban areas and its implementation on parallel architecture. The key point of the proposed model is a cellular representation of the city in order to model streets, gardens, ring roads, buildings, and rivers. Geo referenced image analysis, complemented by database consultation, for example to retrieve elevation data, generates this cellular model. Then, this model is converted into a system made of interconnected processes, which can reproduce many collective behaviors, whether physical or digital.

We have developed a cellular automaton that models sound propagation, including reflection and refraction, working on a graphics accelerator. Finally, we have produced a coupling method between observation systems by sensor networks and physical systems. The social benefits of this work are numerous. We can cite:

- Maps of noise pollution (for example usable for urban planning) : noise pollution/nuisance is an important social and health threat ;
- Alerts regarding critical events: it could be repeated shouts, noise from accidents or explosions, etc. It is then necessary to construct a means of automatic alert, integrating the location of the source and signaling it to the competent authorities ;
- Statistical observation: involves obtaining quantitative and eventually qualitative information, the physical sound itself being information that enables *carrying* other information from a higher level.

Background

The Characteristics of Sound Waves

According to Stanley A Gelfand [1], sound is defined as a wave that travels through the air in the form of a pressure variation, without material displacement. An example is the vibration of the diaphragm in loudspeakers, that transcribes a periodic electrical signal in successive compression and decompression of the air. Sound wave also propagates through solids in the form of tiny vibrations of atoms. There are several types of sound, with regard to human hearing and vibration frequency:

- Infra-sound: below 20 Hz one encounters infra-sound that we do not hear. Some animals such as elephants, giraffes, whales etc., may apply the emit and receive up to 10 Hz ;
- Sounds of 20Hz to 20 KHz are inaudible to humans. According to Blauert [2], is a sound hare a frequencies that our ears can sense and interpret ;

- ultrasound from 20 KHz up until Megahertz : ultrasound lies beyond 20 KHz and goes up to 1000 KHz ;
- Hyper-sound are defined by frequencies beyond several thousand MHz.

Figure 1(a) gives the representations of these different types.

Definition of the Physics of Sound. Sound can be decomposed into elementary sounds that give off wave ”noises”, that are perfectly periodic, and sinusoidal. The equation for the elongation of the sound wave as a function of time is $x = A\sin(\omega t + \phi)$; A is the maximum elongation, ω is the pulsation, ($\omega = 2\pi/T = 2\pi f$) in radian per second and ϕ is the phase shift (in radian) at the initial time t0. The partial differential wave equation (Alembert equation) useful for sound propagation modelling is given by the equation:

$$\frac{\partial^2 u}{\partial x^2} - \frac{1}{v^2}\frac{\partial^2 u}{\partial t^2} = 0 \quad (1)$$

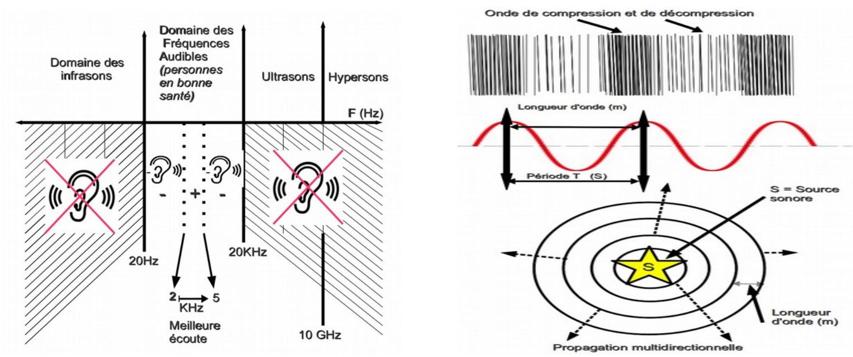
For all ”f” and ”g” functions (assumed regular) there is a solution (with a speed v, but without amortizing or mitigation) which is a function of 2 unknowns, ”x”(spatial) and ”t” (temporal) :

$$u(x,t) = f(x+vt) + g(xvt) \quad (2)$$

If the sound source vibrates in a sinusoidal manner, on the frequency f, the acoustic pressure, at any point P of the sound field (the space surrounding the source) is a sinusoidal function of the time of the same frequency f.

Common Parameters of All Sound Waves. These parameters are common to all wave phenomena. They are: the wavelength, frequency, speed or velocity of propagation. The relationships between these three variables are also common: the speed is equal to the wavelength multiplied by its frequency. If one is interested in pure sinusoidal waves, it is possible to qualify several other characteristics: the original spatial direction, the intensity, also called volume or loudness. Other properties related to perception and composition are: **tonal pitch and spectral pitch**: (corresponds to its vibration frequency), the **rhythm**: (the sound field is the audible movement of the matter of a sound) and the **timbre**: (can be defined as the intrinsic color of the sound, its identity) [2]. The variation of only one of these parameters produces a perception of different sound. In acoustics, the strength of a sound is measured in decibels, it is a quality linked to a simple correspondence with that which the human ear perceives. The sensations of strong, weak, soft or high sounds are linked to the effective value of the sound pressure.

Sound as a Spatio-temporal Phenomenon. There is a direct relationship between space, time and sound: sound travels through space based on a variable time [1]. We recognize three main classes of sounds or acoustic signal: *Impulsive* (signals that are not repeated in time and have a fixed envelope), *Periodic* (signals in which the form is repeated through time) and *Aleatory* (signals which are not periodic). We will pay particular attention to the class of impulsive sound signals in another part of this work.



(a) Different types of sound waves (b) Physical form of pressure waves.

Figure 1. Representation of some backgrounds concepts in sound propagation

Sound Propagation

The displacement of a sound wave from one place to another is the transportation of energy, without the transportation of matter. In a compressible medium such as air, the sound propagates under the form of a pressure variation created by the sound source (figure 1(b)). Only the vibration, without displacing the material, is transmitted from point to point between the object that emits the sound and our ear.

Spatial Properties of Sound Waves. The spatial characteristics of propagation are the following: (i) a wave propagates itself, from its source, in all possible directions; (ii) the disturbance transmits from point to point, according to the current frequency; (iii) the transfer of energy operates without the transport of matter, the waves cross each other without disturbing each other; (iv) the wave propagation speed is a property of the propagation medium.

All sounds (infrasound, sound, ultrasound, hyper-sounds) propagate identically on the same principle. Several changes take place during the transportation of the sound wave: reflection, diffraction, refraction, interference, absorption and diffusion. Parameters related to the architecture of the city as urban barriers to sound propagation (such as walls, streets, trees, parks, etc.) will generate modifications that we will detail.

These main phenomena related to the propagation of a sound wave usually occur when an obstacle is encountered by the wave. Taking into account the complex architecture of a city, our simulations will simplify the parameters by only considering the walls of buildings, trees and open spaces such as streets or parks. In a city, the propagation of sound waves is constantly deflected because the wave is exchanging with the medium and regularly meets obstacles. Propagation is dependent on the nature of the medium in which the sound wave is propagating.

Cellular Automata Formalism

Cellular Automata (CA) [3] constitute a dynamic, discrete space, discrete time formalism. Space in Cellular Automata is partitioned into discrete volume elements called cells and time progresses in discrete steps. Each cell can be in one of a finite number of states at any given time. The ”physics” of this logical universe is deterministic and local. Deterministic means that once a local physics and an initial state of a cellular automaton has been chosen, its future evolution is uniquely determined. Local means that the state of a cell at time t+1 is determined only by its own state and the states of neighboring cells at the previous time t. The operational semantics of a CA as prescribed in a simulation procedure and implemented in a CA solver dictates that values are updated synchronously: all new values are calculated simultaneously.

Related work

In [4], authors discuss the formalism of cellular automata and their relation to the specification of discrete event systems. In this work, both the Cellular Automata (CA) and the DEVS (Discrete Event system Specification) and parallel DEVS formalisms are introduced. Then, a mapping between Cellular Automata and parallel DEVS is elaborated. This fills in the CA-DEVS edge in the FTG (Formalism Transformation Graph). The mapping describes CA semantics in terms of parallel DEVS semantics.

Authors of [5] investigate several aspects for efficiently implementing a sound propagation processor as a non- linear cellular network. Starting from a partial differential wave propagation equation, they define an equivalent cellular array to simulate a certain 2-dimensional scenario space where various obstacles and signal sources may be positioned arbitrarily.

In [6], authors deal with the sound event detection in a noisy environment and present a first classification approach. Detection is the first step of their sound analysis system and is necessary to extract the significant sounds before initiating the classification step. They present three original event detection algorithms. Among these algorithms, one is based on the wavelet and gives the best performances. They evaluate and compare their performance in a noisy environment with the state of the art algorithms in the field.

Approach and Used Techniques

Modeling Techniques

We use cell partitioning and generation techniques to model the urban environment [7]. These techniques use maps, aerial photos and information's collected in geographic information systems (GIS). Thus, we can represent streets, buildings, gardens, waterways, public or commercial facilities (schools, stadiums, shops, supermarkets, etc.). The National GIS propose thus some segments documentation of noise nuisance in proximity to circulation routes [8]. Figure 2 presents two systems of cellular sounds calculated using official GIS Cartelie [8] in the proximity of the University of Brest.

(a)zone 1 (b)zone 2

Figure 2. Two joint sound cellular systems extracted from public mapping

Physical Propagation Simulation Approach

We have chosen a cellular model proposed by Radu and Ioana Dogaru in [5]. The proximity to the cellular automaton being used is a Von Neumann radius 1 with neighborhood cells consisting of North, South, East and West. The variables of state of the cells include the presence of buildings, one or more source (s) sound (s), and physical parameters specifying a sound. The transition function operates on the parameters of mitigation and diffusion of the sound wave, by reconstructing the local developments thereof. A practical realization has been constructed, including cellular systems integrating data from an image extracted from navigation on *OpenStreetMap* in the city of Brest. Each pixel is associated with a zone of a few meters wide depending on the scale of the map, e.g. 45m wide for each pixel for the first simulation shown Figure 5b. It has a map of the buildings in the city provided in the form of shapefile, file format; nearly 80,000 polygons (buildings) represent thus potential obstacles for sound. The simulation allows exploration fictive interactive through a virtual microphone that reproduces the sound simulated after propagation, and all this in arbitrary locations. Before going into the details of the simulation, however, it is necessary to look at the physical nature of sound and its discrete data abstraction.

Simulation of Sound Propagation by CA: Spatial Aspects and Parallel Implementation

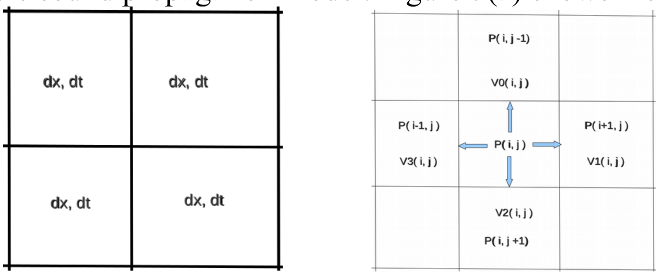
Cellular automata constitute a way to model complex systems such as the phenomenon of wave propagation, diffusion or gas flow. The reason is that the spatial influences are calculated locally like the real physical phenomenon. In a model of propagation simulation by cellular automata, we consider a spatial grid of cells that evolve according to their state and the state of their immediate neighbors. A complete cellular model is a scenario in which the spatial dimension integrates:

—the existence of cardinal directions and positions reachable from the cells; the neighbourhood used for the sound modelling is a Von Neumann of radius 1.

—Changes in the state including the context, barriers, walls, trees as well as noise sources. Regarding the discrete space, it will be necessary to give each cell a transition function to enable the description of its changes and evolution. The space is therefore represented by a planar array of cells. This grid could, however, be constructed in three dimensions. Each cell can, at any given time, be in a finite number of states. The update rules are the same for all cells. Each time the rules are applied to the entire network a new generation is produced. It is interesting to represent parallel behaviour by the parallel execution structures. The cellular automata has therefore been transcribed for a NVIDIA graphics accelerator and programmed in CUDA. At the same time, the structural data for the city has been translated to enable the cellular system to run.

Transition Function: Neighbourhood, Pressure and Speed

Conforming to the proposition put forward by Radu and Ioana Dogaru in [5], we are assuming Alembert’s partial differential equation representing the equations of sound waves (equation 1), then we define the discrete sound propagation model. Figure 3(a) shows the discrete model defined.



(a) Cell Matrices (b) Pressure and speed in each cell

Figure 3. Discrete representation of certain characteristics of sound in a cell

State of a Cell and Transition Function

Each cell is updated at each discrete time step according to a rule of local interaction. First, the particle velocities in the four directions are updated as a function of time, in accordance with the pressure difference between neighbouring cells. The rule for updating is given by: V’a(x, t + 1) = Va(x, t)P(x + dxa, t)P (x, t) [9], is going to represent the particle velocity and P the sound pressure. The position of the cells is expressed as a vector (x) in steps of discrete time (t). The suffix (a) in dxa represents the index of the four neighbours. The particle velocity obeys also :

V a(x, t + 1) = (1d)V a(x, t + 1)

This formula expresses the linear energy dissipation mechanism [9]. This state integrates the sound pressure P. The update of this pressure during the cellular automaton stages is written:

$$P(x, t+1) = P(x, t) - C_a^2 \sum_a Va(x, t+1)$$

With Ca = the speed of waves traveling in the CA area, Va represents the particle velocity and P is the sound pressure. The absorption coefficient (or constant amortizing of the sound in the obstacle) is another parameter of the cell. In the case of air, one uses: d = 0.0001. This coefficient can reach up to 0.8 for current urban obstacles.

The Cell Modelled in the Environment

An average particle size for this simulation is a grid of 1000 X 1000 cells representing one million elements. To obtain a clear idea, we can assume a wave frequency to 10 KHz, corresponding to a period of 100 microseconds. The sound propagation speed is 344 m/s in an atmosphere under normal pressure conditions, and temperature to 20 degree Celsius. The space occupied by a sound pulse is the wavelength of the value of 3.44cm. By measuring a cellular automaton to 10,000 Hz, a grid whose grain is 3.44cm would cross a cell of this size in each period. In Figure 4, the propagation is observed from 3 sound sources composed of interference, diffraction and refraction.

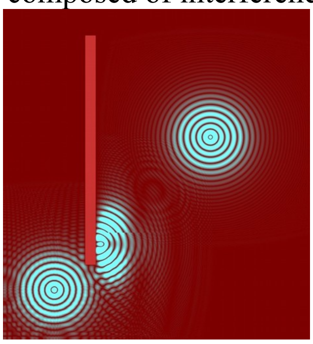


Figure 4. Simulation of propagation of 3 sound sources, with detectable wavelengths (blue stripes) and a red bar symbolizing an obstacle.

The vertical bar illustrates a wall with a coefficient mitigation greater than 0.8 (resistance of the walls). It permits the observation of the phenomena:

- of the interference when the waves trains from the 2 sources meet;

- of the reflection during the contact of the waves with the ”wall”. The period: T = 1/f = 0,0001 s.

The wavelength λ is written as: $\lambda = VT = \frac{V}{f}$

This wavelength is observable in the figure 4: it corresponds to the distance between two blue circles. The pulsation or angular frequency is given by: ω = 2πf = 2π/T. The sound pressure at a point thus calculable.

Representation of the Environment

Here, a preliminary scale calculation using data from the Mercator tile projector, adapts the scale of the map of a city, to the size of CA cells. The meter pixel conversion formula is integrated with laboratory tools (design by P Y Lucas), to directly give the real environmental space measured in meters per pixel. Figure 3(b) shows the discrete model defined for that, and figure 5(a) show the result obtain from the calculating of the size of the cell, with the integration of a Geo-localized map of Brest city.

Geometry of the City and Sound Waves

Here, the physical dimension becomes important, because cellular systems represent real physical objects whose geometrical dimensions are known. Depending on the scale of the overall geographical position of the area of interest or city, we observe different CA cells sizes whose granularity can also be varied. In Figure 5a, the Geo- localization data presented on the top left of the interface conducts a coordinate of 1.586 meter per pixel. Urban structures will behave both as filters and reverberation systems. The instantaneous acoustic pressure is an integration of pressure over a period t_i, it oscillates around the ambient pressure p_a. We consider variations around a stable pressure:

$$p'(t_0) = p(t_0) - P_a = p(t_0) - \int_{t=0}^{\infty} e^{-\frac{t}{T}p(t_0-t)dt}$$

To permit the determination of sound pressure frequencies.

The effects of sound on the ear depend on the power of the sound waves which determines the volume level. The sound power is proportional to the square of the acoustic pressure.

The effective value $P_{eff}(t)$ of the acoustic pressure is calculated over an integration period t_{ii}:

$$p_{eff}(t) = \sqrt{\frac{1}{t_i} . \int_{t-t_i}^{t} p'^2(t)dt}$$

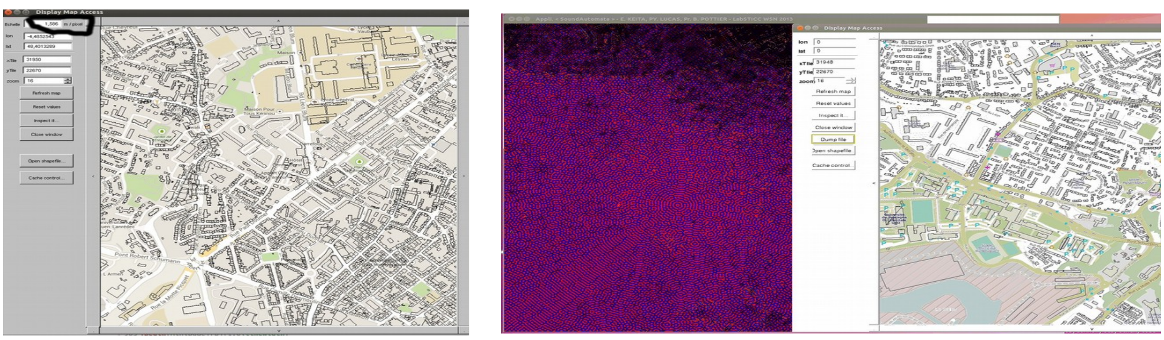
The Sound Level Meters allow the inclusion of the human perception of different sounds to its real sound level by performing a weighing of the results of noise measurements, by frequency [1].

Figure 3b shows the relations between the pressure and the neighbourhood of a cell.

Interpretation of Sound Diffusion

This interpretation is the target of a simulator which generates sound waves in an urban environment. These waves travel from place to place, are reflected or amortized. The findings of these changes are the subject of the simulation, for diagnosing the power of the sound, for example.

Figure 5b presents a case of sound propagation simulation. The map of the buildings is shown on the right, while the mottling to the left represents the pressure pockets of a sound source.

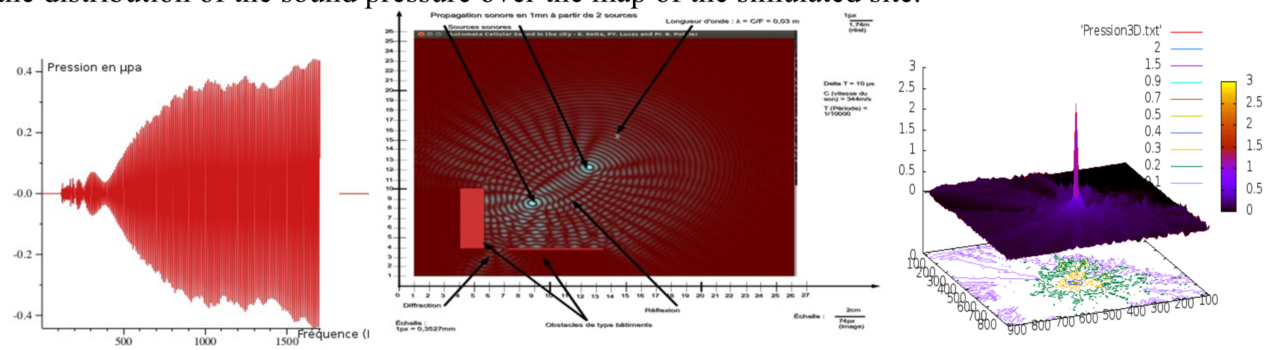


(a)Result with a Geo-localized map of Brest (b)Sound propagation simulation in Brest city

Figure 5. A case of sound propagation simulation in a Brest city

Parallel Execution on CUDA and 3D Representation of a Sound

The implementation of our approach was done, in parallel programming in CUDA environment. Figure 6(a) shows a probe placed in a cell to visualize its contents. Figure 6(b) shows the manual determination of the parameters of interactions and visualization of a sound in cells. Its considers two state variables placed in each cell: the sound pressure ”P” and the speed of particles ”V”. After recovery of the cellular plan, we represent the sound characteristics as volumes. Figure 6(c) shows the distribution of the sound pressure over the map of the simulated site.



(a) Cell contents of 10 KHz, 20 ms (b) Manual calculation of scale and granularity (c) 3D Representation of the pressure in the cell

Figure 6. Some results of execution.

Conclusion and Future Works

Cellular automata are used as a discrete approximation of physical phenomena. By choosing the right time scale and good spatial grain, it is possible to represent a situation and its progress in a realistic manner. We applied this execution model to the propagation of sound in an urban context, showing how one or more sound sources may be controlled for transmitting signals that can be received and analyzed after propagation. The application value of this simulation approach is situated in the diagnosis of events, or in situations that affect social life. The parallel execution model is perfectly well suited to the execution of these simulations, and with a clear outcome, the GPU graphic accelerators.

This paper focuses on the discrete simulation of the sound propagation in urban areas, in the context of the smart city. Its practical applications are numerous, in particular in the field of wireless sensor networks, which are an important element in the current digital landscape. One of the areas mentioned is smart cities. Another of the most cited domains is that of communicating objects that promise important developments. The pervasive sound is an element of this context allowing for example to visit or to monitor distant sites in a diffuse way. The objects ”talk to each other”. The approach may be applied to other physical phenomena, such as light, radio waves (developing special aspects such as longitude and latitude), river pollution, urban noise pollution and In other contexts such as the city, the countryside, the human body (networked micro robots), etc. As future work of this paper, we propose to:

—addressing the problem of relaying sound in the city through sensor networks, to direct the propagation of sound to a specific destination. This will allow the development of local or regional warning sirens;

—apply the propagation of sound for the detection of the propagation of water pollution in a river;

—locate satellite sound sources. This would considerably reduce the time taken to pay for an event signaled by a sound source.

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2nd CMSAM

2017 2nd International Conference on Computational Modeling, Simulation and Applied Mathematics

Acceptance Letter

Paper ID: CM682
Paper title: Discrete simulation of sound propagation in the city based on celullar automaton
Paper Author(s): Eloi B. Keita, Valery M. Monthe, Bernard Pottier

Dear Prof./Dr. Eloi B. Keita,

Thank you very much for your support and submission to CMSAM2017.

We are very glad to tell you that your submission, which has received high praise from the anonymous reviewers, has been officially ACCEPTED by CMSAM2017.

In order to make you understand and finish the registration work, Please log in the register page and following guide carefully: http://www.cmsam2017.org/reg/instruction_en.html

Please find the Acceptance Letter in the attachment, and complete your registration before the deadline (September 15, 2017).

Thanks again for your support and we look forward to your confirmation.

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Review Comments

Criteria (1-Poor, 2-Fair, 3-Good, 4-Very Good, 5-Outstanding)
*Originality: 5
*Significance and usefulness: 4
*Technical Soundness: 3
*Reference to related literature: 4
*Presentation and English: 4
*Match to Conference Topic: 4
*Quality of the Figures: 4
*Quality of Format: 4

Overall Paper Recommendation (Strongly Reject, Reject, Marginally Accept, Accept, Strong Accept): **Accepted**

ACCEPTANCE AND INVITATION LETTER

Dear Dr. Eloi KEITA,

Paper ID: CM682

Paper Title: Discrete simulation of sound propagation in the city based on celullar automaton

Authors: Eloi B. Keita, Valery M. Monthe, Bernard Pottier

Thank you for submitting the above paper to the 2017 2nd International Conference on Computational Modeling, Simulation and Applied Mathematics (CMSAM2017). The website is http://www.cmsam2017.org/.

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As a result of the reviews and revisions, we are pleased to inform you that the paper above has been formally accepted for publication on the above CMSAM2017 conference proceedings. We would appreciate it if you could send the final version of the manuscript at your earliest convenience, to ensure a timely publication of the paper. When you submit the final version, please highlight any changes or amendments made to the manuscript.

Thank you for your contribution to the CMSAM2017 and we are looking forward to your future participation on October 22-23, 2017, Beijing, China.

Welcome to CMSAM2017, and welcome to Beijing!

Yours sincerely,

CMSAM2017 Organizing Committee

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