Holistic Modeling of Embedded Systems with Multi-Discipline Feedback: Application to a Precollision Mitigation Braking System

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***Abstract*—The paper presents the principles, techniques and tools for the efficient modeling and simulation, at the component level, of an heterogeneous system composed of Wireless Sensor Network nodes that exhibits complex multi-discipline feedback loops that are likely to be found in many state-of-the-art applications such as cyber-physical systems. A Precollision Mitigation Braking System (PMBS) is used as a pragmatic case study to validate the whole approach.**

The component models presented (60 GHz communication channel, QPSK RF transceiver, CMOS video sensor, digital microcontroller, simplified car kinetic engine) are written in SystemC and its analog Mixed-Signal extensions, SystemC-AMS, and belong to five distinct yet highly interwoven disciplines: newtonian mechanics, opto-electronics, analog RF, digital and embedded software.

The paper clearly exhibits the complex multi-discipline feedback loop of this automotive application and the related model composability issues. Using the opto-electrical stimulus and the received RF inter-vehicle data, a car is able to exploit its environmental data to autonomously adjust its own velocity. This adjustment impacts the physical environment that in turns modifies the RF communication conditions. Results show that this holistic first-order virtual prototype can be advantageously used to jointly develop the final embedded software and to refine any of its hardware component part.

I. INTRODUCTION

Considering the growing need of consumers for mobile embedded systems that closely interact with their surrounding environment, one of the great challenges of the next decade in the microelectronics industry consists undoubtly in their flawless design. Such complex heterogeneous systems (i.e. "More than Moore") that mix digital and analog electronics as well as various scientific disciplines like newtonian physics, microwaves, optoelectronics... and software can not anymore be realized as the juxtaposition of parts known to work individually. As time-to-market periods dramatically reduce, the ability to model and simulate these multidiscipline systems as a whole, as early as possible in the design cycle and at the highest level of abstraction possible, reduces architecture exploration issues and design errors, while offering enormous advantages in terms of software/hardware codesign, therefore becoming the keystone of successful design methodologies.

However, major industrial and academic players in their relative domains are today still confronted with the lack of simulation tools that can be used efficiently by system designers with various educational backgrounds to conceive and produce such state-of-the-art systems. In particular, cyber-physical systems featuring a tight combination/coordination between the system's computational and the physical elements exhibit by nature complex feedback loops that can yet hardly be captured in currently available design environments, especially when it comes to integrate software in these loops.

This paper is an attempt to demonstrate the joined interest of SystemC and its analog Mixed-Signal extensions, SystemC-AMS, to capture, model and faithfully simulate these feedback loops. As an illustration example, a Precollision Mitigation Braking System (PMBS) for the automotive industry is presented. This system exhibits an interesting feedback loop where mechanics, opto-electronics, analog RF, digital and software are tightly intertwined. The corresponding submodels have been developped especially for the application (complete 60 GHz QPSK baseband RF transmission scheme, video sensor) or reused from previous designs (digital, embedded software templated microkernel).

The paper is composed of 6 sections. Section 2 presents the related work, both in the areas of heterogeneous modeling and inter-vehicle communication. Section 3 introduces the user's view of the PMBS application case study while section 4 presents the corresponding model designer's view and focuses on the interaction between constitutive parts. Section 5 describes the experimental setup and provides simulation results. Section 6 concludes the paper.

978-3-9810801-8-6/DATE12/©2012 EDAA

II. Related Work

On one hand, as part of Intelligent Transportation Systems (ITS), a lot of studies have targeted the Inter-Vehicule Communication (IVC) both from the academic and the industry [1]. Their common approach is to assume that all vehicules are equipped with RF transceiver capabilities, enabling inter-vehicule communication. One of the major goal of IVC is to increase safety by taking advantage of dissemination of warning information [2], [3]. Therefore a lot of interest has been focused on dedicated protocols matching the requirements of safety automotive applications [4]. These studies operate at the protocol level without any actual interaction with the hardware.

On the other hand, the field of Wireless Sensor Network (WSN) has also attracted research attention, often targeting the power consumption optimization. Since such WSN can run out of energy, they are dedicated to in-car non-safety critical application [5] in the automotive field.

Yet, to handle safety features in-car the hardware and the embedded software [6], [7] have to interact closely with the warning information spread by the other cars. To investigate such complex heterogeneous system, operating multiple feedback between software and multi-domain hardware, the AMS extension of SystemC is a good candidate [5], [8], [9], [10]. The application case study detailed hereafter has intentionally been kept simple and clearly does not contain any innovative component, but the whole point is to offer system engineers a complete, proven, workflow to design heterogeneous virtual prototypes mixing physical disciplines and software.

III. Application Case Study

The presented heterogeneous system is a direct application of Inter-Vehicule Communication (IVC) principles for road safety by dissemination of warning information [2]. In the automotive industry, such a system is called a Precollision Mitigation Braking System (PMBS) [3].

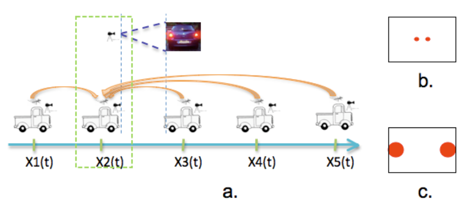

Fig. 1. The modeled PMBS system, user's view.

In this paper, the PMBS is modeled and simulated at the component level and actually corresponds to a wireless sensor network where each node represents a car i moving, at night, at velocity v_i and acceleration a_i on a flat rectilinear road, as shown in Figure 1a. This component-based modeling approach allows for the refinement at any time of any of the system's constituent parts.

d_{ij} and v_{ij} respectively represent the distance and relative velocity between car i and j. The vehicles are all equivalent and are not allowed to overtake each other. Each vehicle is equiped with two red tail lamps (turned on), a 320x200 pixels color video sensor at the front, and a 60 GHz RF transceiver for inter-vehicle propagation of meaningful kinetic values for each car. Periodically, each car sends its kinetic information and distance estimation to all other cars, allowing them to locally rebuild a quite accurate representation of the traffic. The video sensor captures the two red light cones emitted by the preceding car and generates a digital color bitmap image in a memory buffer. Figures 1b and 1c respectively show video sensor images corresponding to the far and near vehicles situations.

The image buffer is stored in a 32-bit microcontroller memory that can be accessed directly by the embedded software in order to compute an estimate of the distance with the upstream vehicle. Considering several successive sensor frames, it is even possible to calculate an estimate of the relative speed with the preceding car.

To prevent several vehicles to emit RF data at the same time, a simple Timed-Division Multiple Access (TDMA) scheme is used. A given car is allowed to send information if and only if it has gained the TDMA token. A special RF token is sent periodically to resynchronize the RF receivers.

IV. Modeling the Whole System

The global PMBS system, detailed in Figure 2, has been completely modeled in SystemC and its analog Mixed-Signal extensions, SystemC AMS [9]. The model addresses 5 tightly coupled disciplines, each characterized by its number in the figure: newtonian mechanics (1), opto-electronics (2), analog RF (3), digital electronics (4) and embedded software (5). Shades of grey indicate the points of interest, the interdisciplinary interfaces exhibited in this paper.

The top part (Part 1, Physical environment) of the figure represents the physical environment, i.e. physical reality. It is modeled in SystemC-AMS Timed-DataFlow (TDF), receives the real kinetic data from the kinetic engine of each car, and is responsible for generating the image stimuli for each car, for gathering the real kinetic data of all cars and for propagating these data to the RF communication channel.

The bottom part (Part 2, Communication channel) represents the 60 GHz communication channel. The channel, also modeled in SystemC-AMS TDF, receives as inputs the RF transmitter outputs of each car as well as all the kinetic data (inter-vehicle distances and relative velocities) that considerably impact the channel behavior. The communication channel is responsible for generating the RF output data that is propagated to each car RF receiver.

The middle part (Part 3, Car wireless sensor nodes) of the figure corresponds to the Wireless Sensor Nodes representing the cars. A car is mainly characterized by its digital control that runs the embedded software and reacts to an external video sensor event (a new video frame has been received) emitted by the video sensor, to an external RF event (an RF message emitted by another car has been received) emitted by the RF transceiver, and to an internal timer interrupt event (used to compute the owner of the TDMA token). The digital

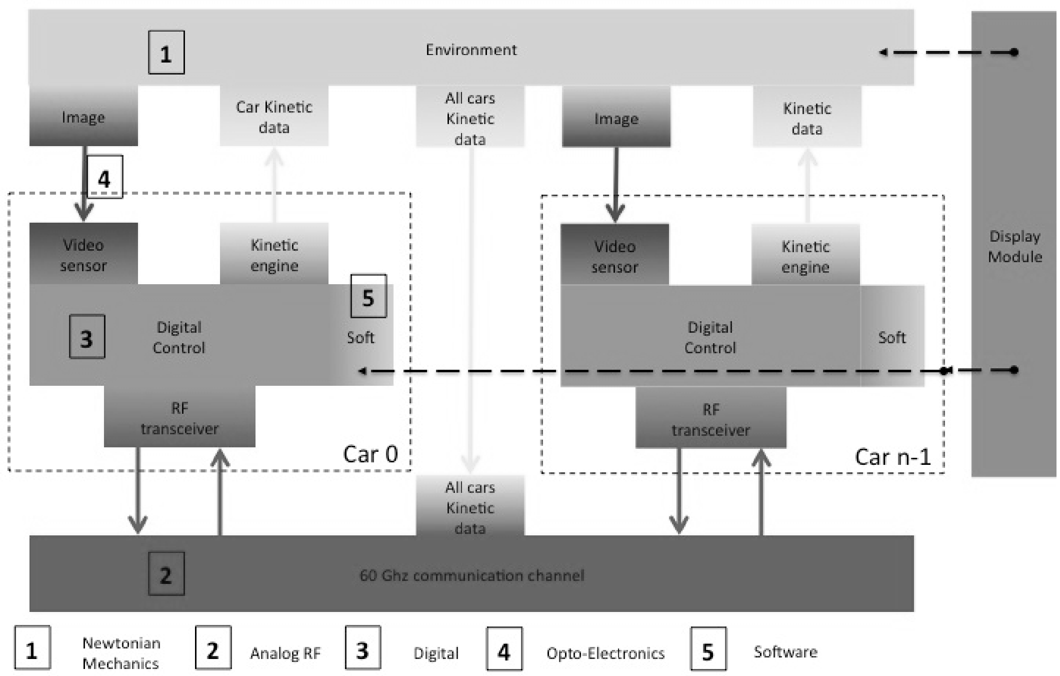

Fig. 2. The modeled PMBS system.

components used in the virtual prototype are standard and not discussed in the paper.

The left part (Part 4, Optoelectronics) of the figure relates to video sensor and image stimuli generators, while part 5 corresponds to the embedded software.

Figure 2 clearly exhibits the complex multi-discipline feedback loop presented in the paper. Using the opto-electrical stimulus (i.e. Reading Video Sensor and calculating the inter-pixel distance) and the received RF data (i.e. Reading RF transceiver receiver), a car is able to adjust its own velocity (i.e. Writing to kinetic engine). This adjustment impacts the physical environment (i.e. Write to Environment) that in turns modifies the RF communication conditions (i.e. Write to Communication channel). It is worth noticing that the environment and RF parts are tightly connected through the kinetic data and thus considered altogether from a simulation viewpoint.

After elaboration of the whole system model (just before the simulation starts), and by means of a configuration file, each vehicle i is assigned its initial position on the road x_i, velocity v_i and acceleration a_i. RF can be activated or not, allowing many different simulation scenarios with open or closed feedback loops.

A. Software

The embedded software running on the processor is written in C language and is cross-compiled with GNU GCC with MIPS32 as a target. The default state of the embedded application is idle. It only wakes up when one of the 3 possible interrupts is received by the processor. The serializer/deserializer component generates an interrupt when a RF message has been received. The message is then decoded and written to a simple message structure. The message contains the emitting node identifier, some emergency brake flag information and the estimated distance with the preceding vehicle. With these data, two software tables are updated: the first one for the distance between each car and the second one for the emergency brake command. Using these tables, each vehicle can get an estimate and regularly updated vision of the road.

When an interrupt is generated by the video sensor (i.e. a new image has been captured), a simple C function calculates the distance with the vehicle ahead. This calculation consists in counting the number of non-red pixels separating the two red tail lamps in the captured image. Using a look-up table dereferencing technique, this number gives, with a noticeable loss of accuracy, the distance with the preceding vehicle. The relative velocity can be calculated when a sufficient number of image have been processed. Using these 2 values, the Time To Collision (TTC) is then computed. The TTC is the ratio of the distance d_{ij} divided by the relative vehicle velocity v_{ij}: $TTC = d_{ij}/v_{ij}$. An emergency brake command is sent to the kinetic engine if $TTC <= 1s$. Additionnaly, if $TTC <= 2s$ and if the vehicle has received RF information telling that the vehicle ahead is breaking, an emergency brake command is also issued.

A timer is setup to raise a hardware interrupt every 1ms.

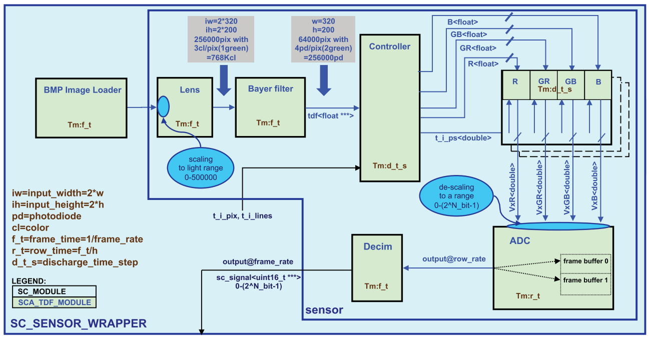

Fig. 3. The TDF model of the video sensor.

Each instantiated node has a temporal slot associated which can be used to broadcast its local vehicle data message to every other nodes. If the slot is the one associated to the node then the pending RF message, if available, is sent.

B. Video Sensor

The CMOS video sensor used in this application is designed by STMicroelectronics in its IMG140 CMOS technology. The size of each pixel of the matrix is 1.4μm x 1.4μm. Each pixel is a 1T75 type pinned photodiode with correlated double sampling (CDS). The transistors are shared among the 4 neighboring pixels leading to a 1.75 equivalent transistors per pixel [10]. Four photodiodes share the reset, source follower (SF), and readout (READ) transistors to increase the fill factor. Each photodiode has its own transfer gate (TG). The full matrix can count up to 2 mega pixels (1920x1080) but has been reduced to a 320x200 for the sake of simulation performance. The ability to perform an analog binning of the pixels before the sampling of the column lines allows to have different output frame rates. The sampling is performed by a set of 10-bit ADCs.

The SystemC-AMS video sensor model corresponds to the TDF cluster of Figure 3. The frames of the video stream are passed from block to block in the chain. The first element of the chain is the image sent by the TDF module environment. It is then coded upon a parametric number of bits and sent to the lens module. The image passes through a Bayer filter (BF) module which, in turn, sends it to the inner part of the pixel model. The TDF time step is reduced to the discharge time step and the whole matrix is represented by an array of pixel instances. The controller drives the whole array with the light signals coming from the Bayer filter. The light signals are updated at the beginning of each frame processing. The pixel contains four photodiodes driven by the four light signals and the integration time information, each pixel column provides the input signal to be sampled by the ADCs. Finally, a decimator is needed to convert the row rate TDF signal into a frame rate signal suitable for the SystemC digital interface.

C. Environment

The environment subpart is connected to the kinetic engine of each vehicle from which it gets the location of the car on the road. With all the locations gathered as a whole, the environment component can send to each vehicle the corresponding image that will be processed by the vision sensor. All the visual stimuli images have been precalculated and stored as an array of bitmapped images indexed by the distances.

D. 60 GHz communication channel and RF transceivers

Simulation of wireless communication is often done using the passband simulation model which requires huge memory ressources and long time of simulation. Furthermore, the demands on system level simulation of heteregeneous complex systems are being more and more important. Thus, faster model of simulation is required. Equivalent baseband simulation model is a promising solution. In fact, it offers many advantages over the passband simulation model:

- Baseband simulation takes much less time to process the same number of symbols rather than passband simulation.
- Equivalent baseband model is a behavioral model and it depends on few parameters compared to passband one. However, they are accurate enough to model RF devices.

Therefore, the used RF devices and the wireless channel models are equivalent baseband models.

1) RF transceivers: The RF transceiver is based on QPSK modulation. It consists of three parts: DSP, analog and RF. The main functionalities of DSP are encoding, decoding, digital filtering (square root raised cosine shape filter and adaptif filter), equalization (Minimum Mean Square Error (MMSE) channel equalizer). The analog part consists of Sigma-Delta DAC and ADC. Processes applied to the analog signal in the RF front end include amplification (PA, LNA) and mixing (LO, MIXER). These processes add various impairments to the transmitted and received signal. The non-linearities added by each RF component are static polynomial models.

2) Wireless communication channel: The channel model used in this application derives from the wireless multipath channel model. This model consists of four contributions: propagation path loss, log-normal shadowing, multipath fading phenomenon and additive white Gaussian noise contribution.

a) Pathloss: Path loss is defined as the difference between the received power and the transmitted one. It depends on the distance between transmitter and receiver. When the medium/environment between them has no obstacle, but simply a direct line of sight (LOS), the free space path loss L can be expressed below in dB form, where distance d is measured in Km and the carrier frequency f is given in MHz:

$$L_{dB} = 32.4 + 20.\log(d_{Km}) + 20.\log(f_{MHz}) \qquad (1)$$

b) Shadowing: The second mechanism used to characterize the wireless channel is called log-normal shadowing. Shadowing occurs when the LOS component is obstructed between transmitter and receiver due to either large buildings, terrain and so on. The presence of these obstructions has a direct incidence on the mean received signal [11], [12], [13].

The method used to model the log-normal shadowing is based on lowpass filtering (LPF with IIR structure) of White

Gaussian Noise (WGN) source. Assuming u the shadowing source that will be multiplied by the RF transmitted signal, it can be expressed as:

$$u(k+1) = \alpha_d \cdot u(k) + \sigma\sqrt{1-{\alpha_d}^2} \cdot n(k) \quad (2)$$

where σ is the standard deviation measured in dB and α_d the correlation between two samples function of their spatial distance and the vehicle velocity.

For example, in the suburban environment $\sigma = 7.5dB$ with a correlation of approximately 0.82 at a distance of $100m$.

c) Multipath: Signals transmitted between transmit and receive antennas will undergo various power fluctuations. These signal variations become visible through the use of antenna where several paths are summed together. These paths enter the antenna after having traveled routes and encountered reflections and diffractions due to surrounding obstructions. The received signal thus experiences random fluctuations in both amplitude and phase [14]. Assuming $s(t)$ and $r(t)$ are respectively the signal in the input and output of the multipath fading channel:

$$r(t) = \sum_{k=0}^{N-1} \beta_k(t).e^{j.\phi_k(t)}.s(t-\tau_k(t)) \quad (3)$$

where $\beta_k(t)$, $\phi_k(t)$, $\tau_k(t)$ are respectively the amplitude, the phase and the time of arrival of the k_{th} ray.

An equivalent representation of the baseband channel can be obtained using tapped delay line (TDL) model. The time-variant criterion of the channel is implemented either using Filtered Gaussian Noise (FGN) model [15] or Sum of Sinusoides (SoS) model [16], [17].

V. Experimental setup, design problems and simulation Results

From a SystemC AMS perspective, and because of the feedback loop between the stimuli generator (environment) and the RF channel of Figure 2, all the non-digital components belong to the same TDF cluster by default. This cluster is therefore huge and hardly schedulable by the SystemC AMS scheduler builder because of the varying physical time constants of the different components (second for kinetic data, picosecond for RF). The retained solution to make the simulator work is to split the TDF cluster into two separate and individually scheduled clusters, by inserting convenient discrete-event converter ports to actually exchange the kinetic data. This simulation artifact, while introducing unnecessary conversions with the discrete-event domain, greatly simplifies the scheduling issues in SystemC AMS TDF.

In order to validate the simulator and the interest of the designed PMBS system, three experiences have been conducted using the proof of concept simulator provided by Fraunhofer [18]. In the first scenario, four vehicles c_0 to c_3 have an initial velocity of 27.8m/s (100Km/h) and are spaced out by 20 meters. RF is deactivated and a car c_i only sees car c_{i-1}. This corresponds to an open loop situation. The leading vehicle on the road (c_3) starts to brake at the beginning of the simulation. The locations x_i of the 4 vehicles as a function of time are plotted on figure 4. One can see that the inaccuracies induced by the loose software-based estimation of the distance with the preceding vehicle directly impact the distances when all velocities become null.

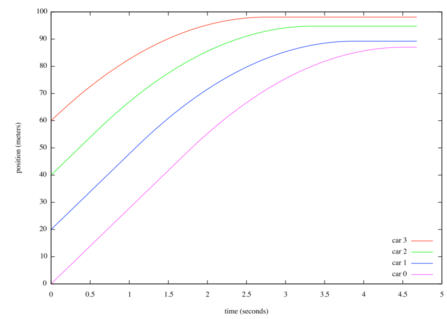

Fig. 4. 100Km/h without RF

In the second simulation, initial velocities have been set to 41.7m/s (150Km/h) and RF is still deactivated. In these conditions, the simulation shows that vehicles collide (Figure 5).

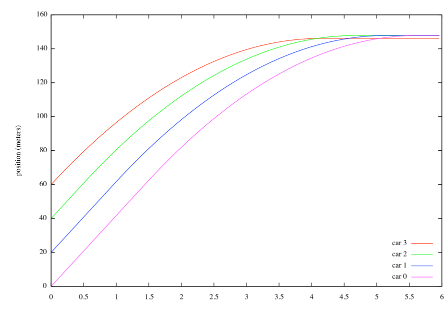

Fig. 5. 150Km/h without RF

In the third scenario (Figure 6), the RF is activated and RF messages are used to propagate an emergency brake command for each car.

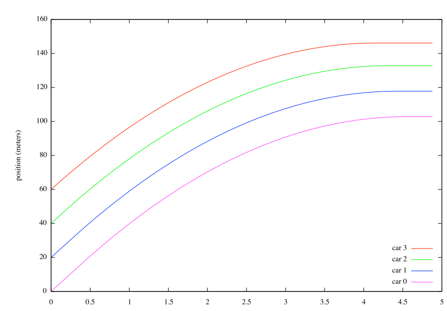

Fig. 6. 150Km/h with RF

The initial velocities are still 41.7m/s, but the feedback loop is now closed and all the vehicles get a faithfull representation of the traffic. Cars slow down and stop smoothly.

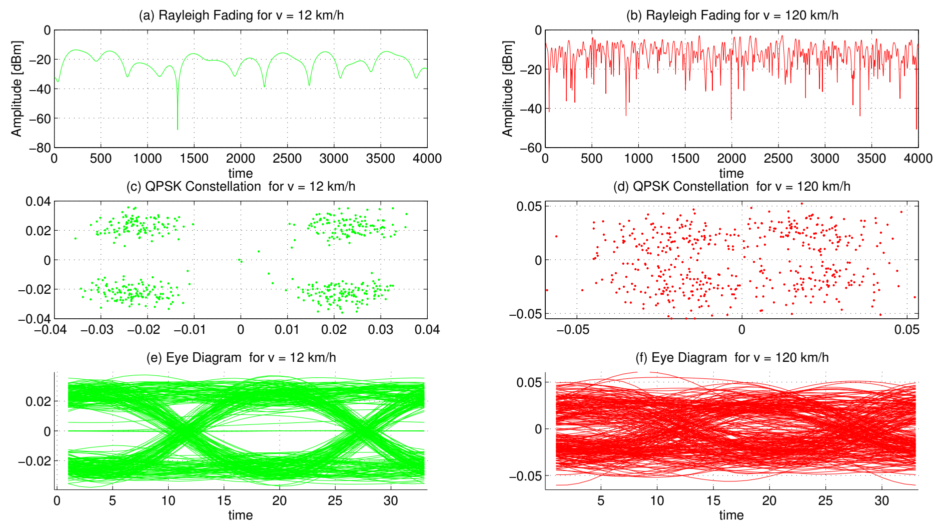

Fig. 7. Evolution of the channel coefficient (Rayleigh fading) (a) @ 12 km/h and (b) @ 120 km/h and its impact on the QPSK constellation (c) and (d) and on the eye diagram (e) and (f).

With 4 cars, the topcell instanciates 40 digital component models and 80 SystemC-AMS TDF models. The required time to simulate 5s of real time on a 2.53GHz dual-core processor is 12m20.224s.

Figure 7 shows the received signal constellation (Fig. 7-c and Fig. 7-d) and the eye diagram (Fig. 7-e and Fig. 7-f) after encountering the multipath faded channel for two different speeds (12 km/h: Fig. 7-a and 120 km/h: Fig. 7-b).

The most important point which should be mentioned is that when the signal encounters a fast fading (greater velocity), the signal amplitude decreases and the phase changes sharply. This causes a rotation of the signal constellation and affects the eye diagram: its opening is reduced so that the time over which the received signal is sampled is reduced and the resulting sample is more sensitive to noise.

VI. Conclusion

The paper shows that the holistic simulation of an heterogeneous system that encompasses several physical domains is not only possible with open-source tools but also gives excellent results in presence of complex feedback loops involving simple newtonian physics, opto-electronics, digital, software and RF. Model interoperablity and performance, obtained through the use of C++, SystemC and SystemC-AMS, and simulation times (when using state of the art RF modeling techniques) are signs of the robustness of the approach. If used in the way it is meant to be used, i.e. as a first-order simulation tool, the duo SystemC/SystemC-AMS offers great possibilities in terms of architectural exploration, codesign and possibly refinement. Most of all, the presented virtual prototype can be used to develop the most compulsory part, the embedded software, way before the the real hardware platform becomes available.

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