Improving Event Transmissions via Novel Multiuser Communication Scheme

Pedro E. Gória Silva*¶, Plínio S. Dester†, Harun Siljak‡, Nicola Marchetti‡,
Pedro H. J. Nardelli*§ and Rausley A. A. de Souza¶
*Lappeenranta–Lahti University of Technology, Finland, email: pedro.goria.silva@lut.fi, pedro.nardelli@lut.fi
†State University of Campinas (Unicamp), Brazil, email: pliniodester@gmail.com
‡Trinity College Dublin, Ireland email: harun.siljak@tcd.ie, nicola.marchetti@tcd.ie
§ University of Oulu, Finland
¶National Institute of Telecommunications (Inatel), Santa Rita do Sapucaí, Brazil. E-mail: rausley@inatel.br

***Abstract*—This work introduces a new perspective for physical media sharing in multiuser communication systems by proposing a novel scheme that enables the recovery of the content of the transmitted message whenever collisions happen. An alarm monitoring system is taken as a merely illustrative toy-model, but indeed the framework is generally applicable. In this scenario, the alarm system is designed to first decide whether a predetermined event has happened over a certain period; if such an event has been identified, the decision node also needs to correctly classify from which sensor the message comes. Simulations corroborate the effectiveness of the proposed method in terms of the event transmission efficiency, when compared with variations of conventional methods like TDMA and slotted ALOHA.**

***Index Terms*—Multiuser communication, medium access control, wireless sensor network, event-triggered communication, semantic communication, goal-oriented communication**

I. INTRODUCTION

Under the umbrella of Wireless Sensor Networks (WSNs), a distinct class of sensor nodes that operate by event-driven (or event-triggered) data acquisition has emerged in recent years [1]. With the goal of reducing the amount of data acquired and transmitted by sensor nodes, the event-driven approach—when properly designed—provides an efficient way to acquire continuously sensed data [2]. In contrast to traditional periodic sampling techniques, the event-driven approach corresponds to nonperiodic sampling. Roughly speaking, event-driven data acquisition is based on the fact that the event-sampled signal can be properly reconstructed (in terms of specific error functions) as long as one is aware of the occurrence of a specific event. For example, such an event could be an overtemperature measured by a particular sensor or electricity metering.

Another fundamental issue for multiuser networks is physical media sharing. Specifically, we are interested in the communication from a potentially large number of sensors to a central node (gateway) forming a many-to-one topology with physical medium sharing. To solve this issue, a wide range of Media Access Control (MAC) protocols has been proposed as a way to deal with possible collisions by controlling which nodes can access the network shared resources, and/or allowing for retransmissions [3], [4]. The simplest solution is to use random access protocols like ALOHA, where nodes transmit whenever they have a packet. The downside is that the network performance in terms of throughput is maximized with a relatively high number of collisions. As expected, whenever a collision happens, the network resources, including energy, are wasted (although the network performance is optimized). To mitigate this issue, some MAC protocols have been designed to establish collision-free communication, which can only be achieved through overheads, centralized resource allocation, and/or contention-based protocols. Those issues are well-known in the literature as presented in [3].

Some new concepts and related technologies have emerged over the last few years, specially in upper-layer network control as, for example, semantic-plane protocols [5] or software-defined networks [6]. Grant-free access in cellular networks focusing on machine-type communication has also been studied in [7], [8]. In this context, a very recent and promising approach is *semantics-empowered communication*, whose ambitious aim is to change the widespread "agnostic" paradigm of communication engineering to allow a timely generation and provision of information to the correct processing point [9]. In this approach, the data are quantitatively measured in terms of their importance, and the reading and transmission of data are then regulated by this metric. The results demonstrated a significant reduction in the traffic load among other improvements.

Despite the unquestionable importance of the above-mentioned approaches, they diverge considerably from the concept we propose here. In fact, our objective is to propose a radical change in the established way of designing wireless communication systems by incorporating both the semantics and function of the data to be transmitted, in some sense modifying the well-accepted layered network models. We consider our approach disruptive for two main reasons: (i) collisions during transmission do not make the transfer of information unfeasible; and (ii) the proposed approach takes advantage of semantic-functional knowledge about the data to design the physical layer.

From left to right in Fig. 1, we have: (i) different signals obtained from the monitored physical processes (e.g., the tem-

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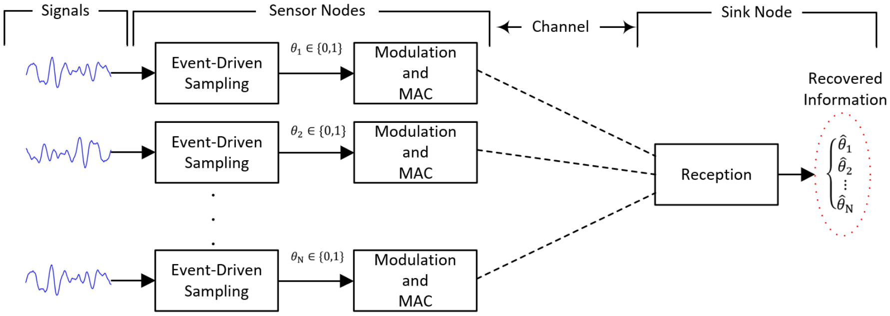

Fig. 1. Block diagram of the main components of the system.

perature in different positions of an industrial plant); (ii) the sensor nodes composed of data acquisition and transmission stages; (iii) a multiuser communication channel; and (iv) the sink node that needs to recover the transmitted information. It is worth noting that in the proposed scenario, the goal of the sink is not to faithfully recover the monitored physical signals, but rather to flag whether a predetermined event at a given sensor has happened. Let us illustrate this by assuming that the physical signal refers to the temperature in a given room. The sensor monitors the signal and only acquires the data if the temperature rises above a given threshold. When it does, this information needs to be transmitted to the sink node through a given communication channel, which is also available to the other users. The sink node needs to indicate if the event, i.e., the threshold crossing, has happened in correspondence of that specific node. This can be formalized as follows. Defining a time interval $\mathcal{T}_n = [(n-1)\tau, n\tau)$, where $n \in \mathbb{N}$ and $\tau \in \mathbb{R}^+$, we can then define the *event function* $\theta_\mathcal{E}(t)$ with $\theta : \mathbb{R} \to \{0,1\}$ indicating whether an event occurred during $\mathcal{T}_n$ on the physical process $\mathcal{E}$. Hereafter, we refer to an event (i.e., $\theta_\mathcal{E}(t) = 1$) occurring on the physical process $\mathcal{E}$ by event $\mathcal{E}$ in order to simplify the notation.

Remark: This scheme is constructed assuming that the information to be transmitted has a well-defined meaning (temperature and safety of the room) that will have a functional role (as part of the alarm system). For this reason, we call this *semantic-functional communication*.

II. FRAMED STRUCTURE OF NETWORK RESOURCES

As will become clear throughout this paper, the proposed physical layer encompasses aspects of modulation, encoding, and MAC in a single layer. In this sense, the proposed design is not an improved version of any existing MAC protocol or modulation technique. The idea we present next is rather to establish a truly semantic-functional communication (SFC) system based on event-triggered sampling for alarm messages.

The proposed approach assumes a framed structure of the network resources. Let $\mathbb{S}$ be a set of N code words associated with each sensor node illustrated in Fig. 1, and thus, the most compact way to represent them is by $k = \lceil \log_2 N \rceil$ bits, where $\lceil \cdot \rceil$ rounds up to the smallest integer larger than or equal to the argument. Within our context, each event $\mathcal{E}$ is defined by a unique set of k bits, i.e., by a code word. Let R be the number of subsets of the shared resource. For example, if the shared resource is the frequency spectrum with a bandwidth W, we would have R subcarriers of width W/R Hz each.

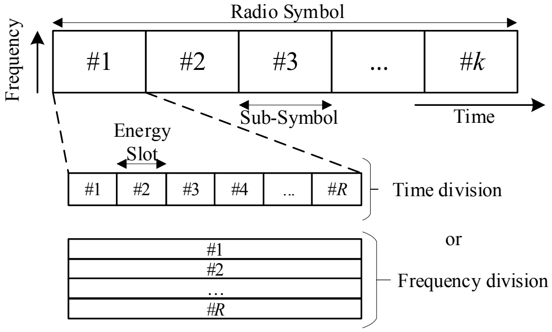

Fig. 2. Radio symbol structure.

Fig. 2 illustrates the proposed structure for the radio frame. We map each code word using only one energy slot per subsymbol; therefore, the receiver must evaluate k subsymbols to make a decision (more details will be provided later in this section). In addition, the receiver must regard any ensemble of k successive subsymbols as one radio symbol. For instance, the next radio symbol with respect to Fig. 2 is composed of subsymbols $\#2, \#3, \ldots, \#k+1$. A subsymbol, in turn, is built out of a set of R energy slots.

The energy slot represents an interval at which the receiver must estimate the signal energy. The receiver does not demodulate the energy slot, because it does not actually carry information as a modulated signal. The goal of the receiver is to determine whether or not there is a signal in an energy slot by estimating its energy. Accordingly, it is not required to synchronize the phase of the local carrier at the receiver. On the one hand, the receiver has the uninterrupted task of detecting a transmitted pulse or inferring that the medium was idle during the duration of an energy slot. On the other hand, the sensor nodes can instantly send the information when they detect an event regardless of channel state.

A. Transmission of a Given Event

Consider a network composed of N sensor nodes that uninterruptedly monitor continuous signals. The purpose of sensor nodes is to recognize whether a given predetermined event $\mathcal{E}$ has happened, in order to feed this information to an alarm system centrally controlled at the sink. As briefly discussed, we consider a multiuser scenario where sensor nodes share the same communication resources, to transmit whether the event associated with the corresponding measurements has happened.

Without loss of generality, we assume frames that are divided only in the time domain. Let us define a discrete version of the event function $\theta_{\mathcal{E}}(t)$ as $\theta_{\mathcal{E}}[n] = \theta_{\mathcal{E}}(n\tau)$ with $\theta : \mathbb{N} \to \{0,1\}$. Note that the sink node can easily build $\theta_{\mathcal{E}}(t)$ from $\theta_{\mathcal{E}}[n]$. By setting the parameter $\tau \in \mathbb{R}^{+}$ as the duration of a subsymbol, we can then create the following event transmission rule: if $\theta_{\mathcal{E}}[n] = 1$ (i.e., an alarm is detected), then the sensor node starts transmitting k subsymbols in sequence starting at a discrete time n.

In order to illustrate how the sensor node manages event transmission, let $\mathbf{Y}_n$ be a $k \times R$ matrix representing the radio symbol at a discrete time n (i.e., the radio symbol whose first subsymbol is in $\mathcal{T}_n$) with the element $y_{i,j} \in \{0, 1, \ldots, N\}$ in the ith row and the jth column representing the energy inside the energy slot j of the subsymbol $i + n$. Further, let $\mathbf{C}_{\mathcal{E}}$ be a $k \times R$ matrix with the element $c_{i,j} \in \{0,1\}$ in the ith row and the jth column. The matrix $\mathbf{C}_{\mathcal{E}}$ then represents the binary mapping of the event $\mathcal{E}$ into k subsymbols (more details will be provided later). To simplify the notation, we henceforth refer to the binary transmission mapping matrix of the event $\mathcal{E}$, i.e., $\mathbf{C}_{\mathcal{E}}$, by the transmission map $\mathcal{E}$. In order to simplify the example, we assume that only two events occur in a discrete time n. Furthermore, we assume that the transmission map for one of these events is given by the matrix $\mathbf{C}_1$ and for the other event given by the matrix $\mathbf{C}_2$. Therefore, the nth radio symbol is given by $\mathbf{Y}_n = \mathbf{C}_1 + \mathbf{C}_2$. In other words, the sensor node, which monitors the signal $\mathcal{E}$, adds energy (i.e., it transmits an unmodulated carrier for the duration of an energy slot) to the respective energy slots of the nth radio symbol in accordance with the values of $c_{i,j}$. Note that the sensor does not need any knowledge of the channel status to transmit.

B. Reception of a Given Event

On the reception side, the sink node needs to correctly identify the occurrence of a predetermined event related to the specific node that transmits it. The recovery of this semantic information is straightforward in our approach, as it does not require any demodulation or data processing (recall that the transmitted message is neither modulated as a waveform nor composed of higher layer overheads). In this case, if the function of the sink is to operate an alarm system based on the occurrence of predetermined events, then all relevant information for that function can be recovered simply by receiving or not a code word. Note that even when no sensor transmits, the sink continues to acquire information about the physical processes, because it can correctly identify if the channel is idle; in other words, silence in the channel is informative in its own right, and the proposed semantic-functional approach makes use of this fact.

The sink node, in turn, must constantly monitor the channel and create a log of the received subsymbols, and then search for valid transmission maps. The process of identifying an event is as follows. Let $\mathbf{H}_n$ be a $k \times R$ matrix containing the last k subsymbols received (i.e., one radio symbol) at a discrete time $n \geq k$ with the element $h_{i,j} \in \{0, 1, \ldots, N\}$ in the ith row and the jth column representing the estimated energy slot (“1” for used, “0” otherwise) j within the received subsymbol $i - k + n$. In order to find out if the transmission map $\mathcal{E}$ was transmitted at a discrete time n, the sink must first perform a point-by-point multiplication between $\mathbf{C}_{\mathcal{E}}$ and $\mathbf{H}_n$ and then count how many non-null elements the resulting matrix has. If the counting result is k, the sink decides in favor of the event $\mathcal{E}$, otherwise not.

The challenge is now to construct a method to generate transmission maps that can uniquely map the event related to a given sensor, which can then be decoded at the sink in the presence of multiple users. The adopted method to map is described in Definition 1.

Definition 1 (Random map)**.** *Let $\mathbf{C}_{\mathcal{E}}$ be the binary matrix with the element $c_{i,j} \in \{0,1\}$ that denotes a transmission ($c_{i,j} = 1$) or not ($c_{i,j} = 0$) during the jth energy slot of the ith subsymbol, to be built as follows. For each row i, only one element $c_{i,j}$ is randomly set to 1. The choice of the element $c_{i,j}$ set to 1 follows a uniform distribution. If one or more code words have the same matrix $\mathbf{C}_{\mathcal{E}}$, one must repeat the mapping process for them until there is no repeated matrix $\mathbf{C}_{\mathcal{E}}$.*

III. COMPARISON BENCHMARK

Regarding the MAC protocol for our comparison benchmark, we opted for the simplest channel partitioning that provides the same channel capacity, namely Time-Division Multiple Access (TDMA) [10]. Note that Frequency-Division Multiple Access (FDMA) and Code-Division Multiple Access (CDMA) could also be employed, but we prefer TDMA because of its simplicity when presenting numerical results.

In our scenario, one could expect that the occurrence of an alarm is uncommon, and thus, the sensor nodes will rarely occupy the resources allocated to them. Thereby, channel partitioning MAC protocols would lead to a system with high channel idle rates and overallocation of resources. One could argue in favor of channel partitioning MAC protocols with dynamic resource allocation. In general terms, the available resources are allocated on-demand to the sensor nodes for these MAC protocols. Therefore, the sensor nodes must somehow request the use of the resource. The control load generated only in the resource request stage would be as costly as the direct sending of information about the event itself, because when requesting the allocation of transmission resources, the sensor node would indirectly be informing the sink about the event. Therefore, higher latency can be expected for dynamic channel partitioning MAC protocols compared to static allocation — note that the high latency is due to the sensor node necessarily requests the use of the medium.

For comparison purposes, let us suppose that the number of available resources is insufficient for a network containing N_t sensor nodes to employ collision-free TDMA, i.e., we have $R < N_\text{t}$. The division of R available resources for this case is carried out as follows. Let $\mathbb{S}$ be a set of N_t code words and $\mathbb{S}_i$, $i \in \{1, 2, \ldots, R\}$, be a subset of $\mathbb{S}$ such that $\mathbb{S}_i \cap \mathbb{S}_j = \emptyset \; \forall j \neq i$. We assume also that the number of elements in each subset $\mathbb{S}_i$ is as close to N_t/R as possible. In order to send a code word from the set $\mathbb{S}_i$, the sensor node must transmit a binary phase-shift keying (BPSK) symbol during the ith energy slot of each subsymbol. Note that a complete transmission of a code word requires k BPSK symbols and thus, k subsymbols.

In addition to TDMA, we also adopted slotted ALOHA for comparison. In this case, we assume that the slot has a duration of $k\tau/R$ seconds, and the packets have a fixed size of k BPSK symbols, thereby maintaining the same power consumption and bandwidth allowed for TDMA and SFC.

IV. NUMERICAL RESULTS

To obtain the numerical results below, we assume that the scenario in Fig. 1 has N statistically independent physical processes and each sensor node monitors exclusively one signal. We also assume that the time interval between the occurrence of the same alarm is exponentially variate with mean $N\tau/\lambda$. Therefore, the total number of observed events across all sensor nodes within an interval $\mathcal{T}_n$ follow a Poisson distribution of mean λ.

We now evaluate the performance of the MAC protocols described above. Numerical results were obtained through Monte Carlo simulations with the aid of Matlab software. TDMA and slotted ALOHA implement the modulation process described in Sec. III. The SFC follows the proposed model, described in Sec. II. We assume an ideal communication channel and postpone further analysis, such as the effects of additive white Gaussian noise (AWGN), fading, and phase error, for future work. Thereby, the impact of collisions on system performance is evident.

We will now define the metric used to assess the performance of our physical layer. We have that $\Pr[\hat{\theta}_\mathcal{E} = 1|\theta_\mathcal{E} = 1]$ and $\Pr[\hat{\theta}_\mathcal{E} = 0|\theta_\mathcal{E} = 0]$ represent the reliability provided by the physical layer regarding the occurrence and non-occurrence of an event, respectively. We will therefore define as follows an efficiency measure aiming to quantitatively evaluate the performance of our physical layer to deliver the desired information about the monitored signals to the sink:

Definition 2 (Efficiency metric)**.** *We can define the efficiency metric as a function of the probabilities* $\Pr[\hat{\theta}_\mathcal{E} = 1|\theta_\mathcal{E} = 1]$ *and* $\Pr[\hat{\theta}_\mathcal{E} = 0|\theta_\mathcal{E} = 0]$ *as*

$$\mathcal{F} \triangleq \Pr[\hat{\theta}_\mathcal{E} = 1|\theta_\mathcal{E} = 1] \; \Pr[\hat{\theta}_\mathcal{E} = 0|\theta_\mathcal{E} = 0]. \tag{1}$$

The rationale for using such a metric is explained next. Suppose that a given event is rare and that the physical layer always interprets that nothing was transmitted. In this case, we would have a high average of correctly received transmission maps. However, the sink would never be able to detect alarm events. On the other hand, by using the proposed metric, we would have $\Pr[\hat{\theta}_\mathcal{E} = 1|\theta_\mathcal{E} = 1] = 0$, and thus, $\mathcal{F} = 0$; therefore, the efficiency $\mathcal{F}$ would capture this ineffectiveness of the physical layer in transmitting the desired event.

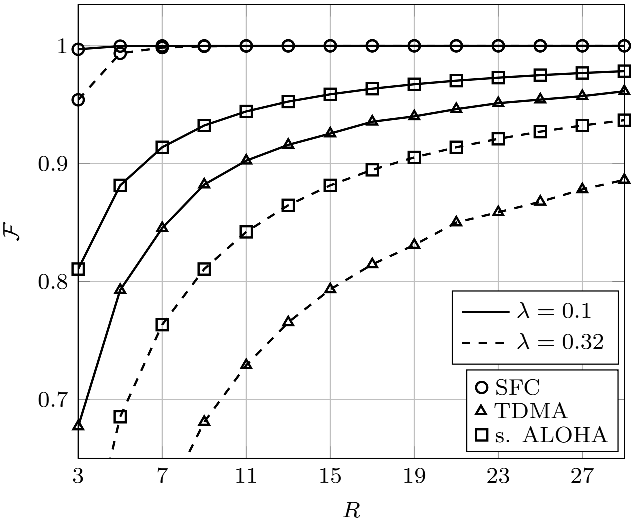

Fig. 3. Efficiency $\mathcal{F}$ of TDMA, slotted ALOHA, and SFC against R for $k = 6$, and $N = 64$.

In Fig. 3, the efficiency $\mathcal{F}$ for TDMA, slotted ALOHA and SFC is plotted against the resource number R. The λ parameter varies as $\{0.1, 0.32\}$, the code word length is $k = 6$, and the number of sensor nodes is $N = 64$. For all cases, as the number of resources allocated to the system increases, the efficiency $\mathcal{F}$ increases; however, the SFC system outperforms the other two. In addition, the efficiency $\mathcal{F}$ of the SFC system gets close to the optimal efficiency (i.e., $\mathcal{F} = 1$) faster than the efficiency $\mathcal{F}$ of TDMA or slotted ALOHA. Note that the SFC system can outperform TDMA and slotted ALOHA even with a higher traffic load (i.e., three times higher λ).

Fig. 4 shows the system performance versus the number of resources R with the ratio $N/R = 6$ remaining constant. Thereby, we can evaluate how systems behave when more users are admitted and mutually more resources are allocated to the system. Again, the SFC system outperforms TDMA and slotted ALOHA, and in addition, it manages to maintain a stable performance. On the other hand, TDMA and slotted ALOHA experience a deterioration in efficiency $\mathcal{F}$ with increasing R and N. As the code word length increases (because of $k = \lceil \log_2 N \rceil$), the channel occupation time for transmitting one code word also increases. Therefore, the probability of a collision in the TDMA and slotted ALOHA systems also increases.

In Fig. 5, the efficiency $\mathcal{F}$ for TDMA, slotted ALOHA, and SFC is plotted against N/R. Clearly, the SFC system outperforms TDMA and slotted ALOHA. The behavior of the SFC system is again remarkable, as in the entire operating region shown in Fig. 5 the SFC system is better than the

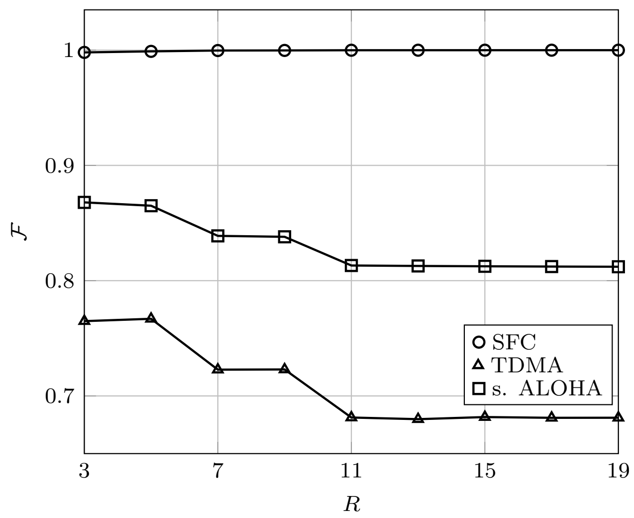

Fig. 4. Efficiency $\mathcal{F}$ of TDMA, slotted ALOHA, and SFC against R for $N = 6R$, and $\lambda = 200/N$.

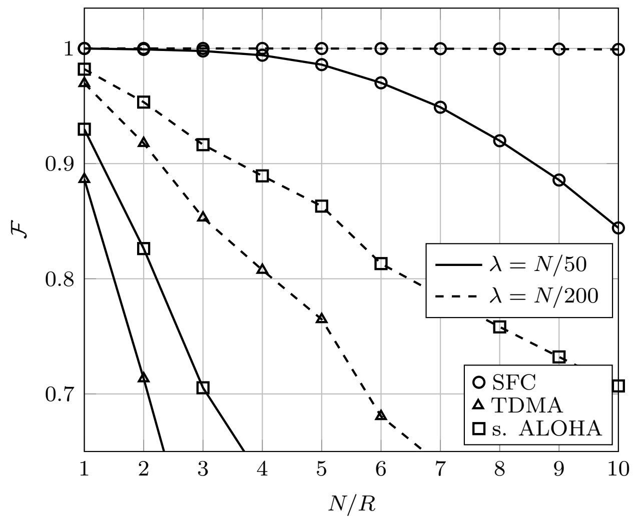

Fig. 5. Efficiency $\mathcal{F}$ of TDMA, slotted ALOHA, and SFC against N/R for $R = 11$.

TDMA and slotted ALOHA systems even with a higher traffic load (four times higher λ). Note that for $N/R = 1$ the SFC system has an efficiency $\mathcal{F}$ of 100%, whereas TDMA and slotted ALOHA do not reach 100% efficiency $\mathcal{F}$ in any of the simulated cases. This is due to the possibility of two or more alarms occurring in the same sensor node within the period of a radio symbol. When this happens, we have a collision for the TDMA and slotted ALOHA systems; however, the SFC system can guarantee that the sink receives the information correctly.

V. CONCLUSION

This paper introduced a novel approach to the design of communication systems based on event transmission. Specifically, we proposed a new scheme using a random map to combine physical and MAC layers. The proposed method constructively handles collisions and requires a low complexity, and our numerical results demonstrated that the proposed semantic-functional communication (SFC) achieved a transmission efficiency of 100% for the proposed application in almost all the studied cases, outperforming the TDMA- or slotted ALOHA-based systems in most of the scenarios evaluated. This initial result will be extended to incorporate a more realistic environment that includes noise, fading, and other impairments of wireless communications. In addition, a thorough theoretical analysis to assess the fundamental characteristics of the proposed system will be presented in future work.

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