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Catastrophic Collision in Bio-nanosensor Networks: Does it really matter?

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***Abstract*—A Wireless Bio-nanosensor Network (WB2N) is a collection of bio-nanodevices having applications in e-health. In this paper, we address the issue of *catastrophic collision* — a phenomenon which exhibits recurrent collisions of femtosecond-long pulse symbols emanating from the nanodevices in a WB2N. Such type of collision is very serious in these networks due to unique properties of the terahertz band (0.1-10 THz). The existing sate-of-the-art on the issue of coordination for medium access by nano-devices is based on asynchronous exchange of pulses by assigning different symbol rates. The existing method of choosing the symbol rate does not completely avoid catastrophic collision. The severity of collision is further pronounced when molecular absorption noise gets compounded. In essence, a few number of collisions, in turn, invites huge number of such events for the subsequent transmission and eventually degrades the whole network performance. So, it is important to handle such collisions for successful execution of protocols of the higher layers. In present work, we analyze the catastrophic collision in detail and model the collision. The preliminary results exhibit the severity of such collisions in the network. It requires immediate attention in order to accept WB2Ns to be successful e-health system.**

***Keywords* – Wireless Bio-nano sensor networks, E-health, Catastrophic Collision, Terahertz Band, Nanotechnology**

I. INTRODUCTION

The long history of medical science and technology has witnessed the incorporation of newer technology [1] for better detection and management of diseases, thereby enhancing the quality of life of patients. The application of nanotechnology in nanomedicine, targeting drug delivery for treatment of diseases such as cancer is becoming very promising in the medical field. The advancement in nanotechnology in the last two decades has provided us the engineering tools to develop nanosensor devices in range of 1-100 nanometers (nm). The capability to detect the events in molecular and cellular levels make the technology very attractive and promising for future e-health. Recent advancement [2], [3] in Carbon Nano Tube (CNT)-based electronics has shown that nanosensors can be equipped with communication and processing capabilities. Hence, nanotechnology opens up a completely new innovative direction for real-time monitoring of life threatening diseases such as cancer with better accuracy and less medical cost [4]. The nano- sized bio-devices can perform only computationally simple jobs, and have limited working region bounded by few several millimeters. However, the use of bio-nanodevices will pronounce a powerful impact if devices cooperatively work in a distributed fashion [5], and the collection of such nanodevices is known as wireless bio-nanosensor network (WB2N).

A. The importance of Bio-nanosensor networks

In the modern world, age-related and chronic diseases such as brain disorders, degenerative neurological disorders such as Alzheimer's, Parkinson's, and cardiovascular disease (CVD) are growing, and it will be multi fold in near future [6]. The study in [7] shows that high mortality rate in adults is due to coronary heart disease (CHD), and cardiovascular disease (CVD). Recently, orthopaedic problems including bone fractures, osteoarthritis, osteoporosis has been shoot up abruptly [8]. To combat such type of diseases, the development of long lasting, biocompatable, cost effective minimally non-invasive devices is in demand.

Deploying nanomaterial-based invasive and/or minimally invasive devices inside the human body and correspondingly processing various physiological parameters in situ and outside is expected to revolutionize patient care. A futuristic e-health monitoring system can be conceived, where various physiological parameters related to fatal and chronic diseases are monitored by WB2Ns, and possibly giving feedback adaptively. One such type of architecture is illustrated in Fig. 1 as an example, where numerous nanodevices are placed on heart, and hips and legs for monitoring the imbalance the cholesterol level, and measuring bone growth respectively on a real-time basis.

B. Communication between bio-nanosensor devices

A very fundamental aspect about WB2Ns to become a successful point of care (POC) system is the communication mechanisms that exists between the bio-nanodevices. Among several proposed schemes, electromagnetic communication, which is based on electromagnetic radiation methodology is very promising and encouraging [9]. Furthermore, the recent advent of CNT-based electronics [10] has demonstrated feasibility of the communication between nanomachines by exchanging one hundred femtosecond pulses with power lying

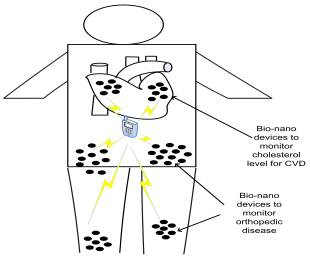


Fig. 1. Architecture of bio-nanosensor networks for monitoring physiological parameters

in the terahertz band. The terahertz band lies between 0.1-10 THz in electromagnetic spectrum for telecommunications. We highlight the characteristics of the terahertz channel in section *C*. Communication in this band works as follows [11]. Assuming the information source as binary, logical "1" is transmitted using one hundred femtosecond pulse and logical "0" is transmitted as being silent. It may be noted that the pulse repetition time is longer than the pulse-width time.

C. Terahertz channel vs. the AWGN channel

Recent efforts on building nano-antennas by means of graphene-based nano-materials has shown the direction to use the terahertz band [12]. The terahertz band is an unlicensed band and communication in this band has not yet received adequate research attention. So, there is huge potential to use the band for communication in the nano-scale. However, recent studies show [13], [14] that it behaves amazingly different from other explored RF band. Jornet et al. [15] observed that the noise in terahertz channel is mainly due to the different resonant frequencies of the constituent molecules. It is prominent when concentration of molecules of the propagation medium is high and/or the distance covered increases. The authors have demonstrated that molecular absorption noise in a standard medium with 1% water vapor molecules behaves differently compared to the classical Additive White Gaussian (AWG) noise, which is observed in the RF band. For example, the noise is colored, i.e., molecules of the medium respond with different resonant frequencies. The important characteristics of this type of noise is that it arises only when the EM waves propagate through the medium [16], and the capacity of the channel falls to zero due to continuous transmission. The reason behind this behavior is that molecules also radiate energy acquired due to the historical transmissions of pulses.

In terms of bandwidth, the terahertz channel provides the entire band for very short range. Since the nano-sensors are extremely energy-constrained [17], and their range of operation is very low, ranging only a few millimeters, multi-hop transmission is suitable and can take advantage of near utra-wide-band capacity of the terahertz band for utra-short distance. In [15], it is shown that the capacity of this channel is in the order of gigabits per second.

D. Motivation

It is important to coordinate concurrent transmissions from multiple nano-machines to realize the potential of multi-hop WB2Ns. The design of MAC protocol in WB2N differs from that of classical wireless sensor networks on three fundamental respects. First, the terahertz band offers a ultra-broad window, almost 10 THz, for ultra-short range, namely for few several millimeters, compared to the classical band-limited wireless network. Second, since the communication in WB2N is based on transmitting short pulses, carrier sensing is not feasible in this case. In contrast, classical Wireless MAC protocols (e.g., IEEE 802.11, SMAC in Wireless Sensor Networks) works on the principle of carrier sensing [18], [19]. Third, the most important characteristic which is highly applicable for WB2Ns is time-varying fluctuation of the stored energy of the nano-device. Since nano-devices themselves are very extremely energy constrained, after few round of communication, the energy contained in them is drained out. However, the energy could be replenished with the help of a novel energy harvesting technique [17], [20], resulting in temporal energy fluctuation of the node. WB2Ns following such type of energy harvesting process is very useful because it could operate for very long time by means of harvesting energy from dynamic and rhythmic activities of organs of human body such as rythmic vibration of heart, and body movements. Considering the distinct characteristics of bio-nanodevices and their operating frequency, Jornet et al [21] presented a MAC protocol which is based on Rate Division Time-Spread On-Off keying (RDTS-OOK). In RDTS-OOK, a tailored modulation scheme suitable for WB2N, bio-nanodevices modulate the femtosecond-long pulses and send those with different symbol rates randomly.

In this context, the following research question arises — *Does the process of sending different symbol rates by different bio-nanodevices invite any collision at the receiver?* The authors in [21] mentioned that collision due to such type of communication is very unlikely; however, they did not demonstrate how catastrophic collision could be serious, by simultaneously taking into consideration the peculiarities of the teraherz band and the energy fluctuation of the bio-nanodevices. Weisenhorn and Hirt [22] showed that the coordination among asynchronous user by allocating different pulse rates to them minimizes the collision probability. However, it requires complex receiver circuitry, and takes the RF channel as the propagation medium.

The remainder of the paper is organized as follows. In Section II, we define catastrophic collision, a severe type of collision, followed by the collision model in Section III. The analytical result is presented in Section IV. Finally, we conclude the paper in Section V.

II. CATASTROPHIC COLLISION

We redefine "catastrophic collision" in the context of W2BNs. It includes not only sequential collision of symbols of a same packet but also the sequential collision of symbols from different packets. This type of collision occurs when a nano-device initiates its transmission randomly in the interval when the molecular absorption noise is at its peak, or the energy of the receiver is empty. So, the subsequent transmission of the symbols increases more noise, and, therefore, invites more collisions. As a result, the relaxation time to diminish the molecular vibration takes longer time, and, hence network performance such as delay, and throughput degrades abruptly. Moreover, the complexity of catastrophic collision gets compounded due to the use of ON-OFF modulation scheme. All types of collision do not lead to an increase in the molecular absorption noise. For example, the collision between the “silent” and “logical 1” pulses, which does not increase the molecular absorption noise, although the receiver can detect the pulse for “logical 1”. However, it cannot extract the information from the silence bit in this case. So, the transmitter which sends the silence bit treats it as a collision.

In accordance with the recent progress on the development of harvesting energy, notably the work of Wang [20], we assume that the nanodevices will harvest energy from their surrounding environment. For example, it is highly desirable that an implantable biomedical device can harvest energy from vibration, rhythmic movement of organs, and limbs. However, in the process of harvesting energy, the nanodevices remain unavailable for some duration. So, the energy of the devices fluctuate over time. However, the energy harvested in this process is very less (in order of picojoul), and the energy content is a precious matter for every bio-nanonode. So, the life-time of WB2Ns gets prolonged (theoretically infinite time).

For the sake of illustration, we present four scenarios as in Fig. 2, where we want to emphasize the existing solution to cope with catastrophic collision is inadequate. In particular, an interesting case occurs when symbols are sent with different rates at different time instants. It occurs that catastrophic collision is likely severe when the contents of data packets of the transmitters have similar pattern.

III. ANALYSIS OF CATASTROPHIC COLLISION

We observe that two important factors are responsible for such type of collision. The first is the behavior of the terahertz channel, and the second is the energy fluctuation of the receiver. Following the same line of argument presented in [23], we consider that the energy of receiver node can be modeled as a *nonstationary continuous-time Markov process*, where the states are defined as a result of combined energy harvesting and consumption mechanisms. From a collision perspective, the states of the receiver node can be grouped into two: “ON” state, which refers to the capability of the node to receive symbols, and the “OFF” state, which refers to the shut-down phase of the node due to void of energy. The same argument holds for the terahertz channel. The “GOOD” state of a channel refers the good case, when the symbol does not undergo any significant molecular absorption noise, and the symbol can be detected at the receiver end with higher probability; whereas, the “BAD” channel state refers to the condition when the symbols die out due to huge molecular absorption noise. These two conditions are shown in Fig. 3. On the other hand, it is reasonable to consider the generation of pulses of the transmitter as Poisson process; whereas, the arrival of symbols (or pulses) at the receiver is inhomogeneous Poisson process.

As previously stated, collision appears not only in the middle of transmission when the receiver suddenly goes to the “OFF” state, but also the case when terahertz channel experiences high level of molecular absorption noise. So, the catastrophic collision is the result of both the dynamic distortion of the channel and the energy fluctuation of the receiver. The important observation we make is that the behavior of the channel and the fluctuation of energy are independent. Apart from this, the following question arises — Can we predict the quantitative behavior of the channel? The answer is not so straight forward. It requires information such as how many transmissions occurred in the past, how many going on at present, and how many will occur in the near future, and the composition of the medium’s constituent molecules. In our present work, we analyze collision in the case when the receiver goes to “ON” and “OFF” state according to the profile of energy content. Both the states, “ON” and “OFF”, follow exponential distribution. Following the method mentioned by Lee [24] for availability analysis of arrival of random-request tasks we model the above-mentioned problem.

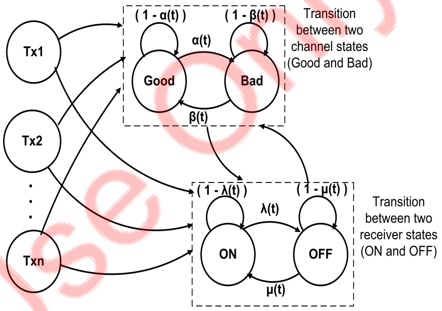


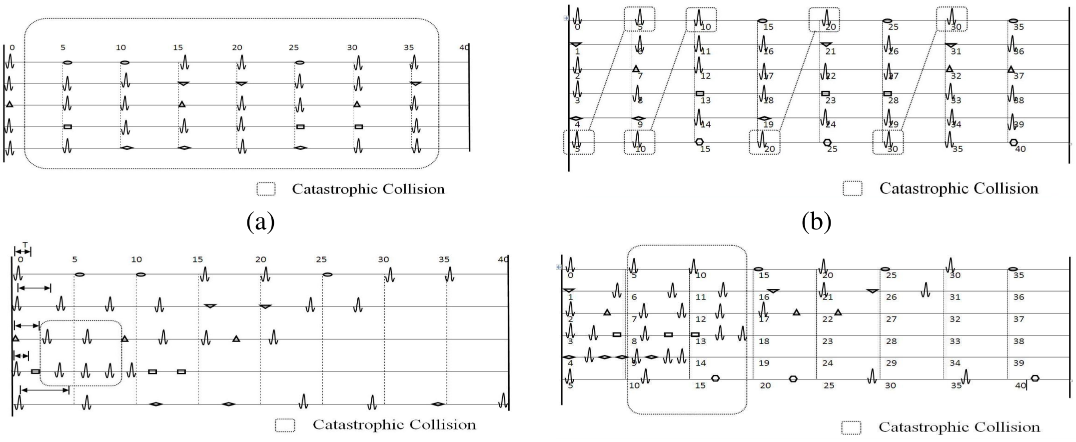
Fig. 3. Modeling of Receiver node and Terahertz channel as 2-state Markov process, as viewed from the catastrophic collision perspective.

Now, the probability of receiver to be in the “ON” state for j out of k symbols is $P_{i,j}(t_1, t_2, ..., t_k)$, assuming each k^{th} symbol arrives at t_k time, and is written as follows:

$$\begin{aligned} P_{i,j}(t_1, t_2, ..., t_k) = \sum_{\omega_1} Pr\{I(t_1) = i_1, I(t_2) = i_2, ..., \\ I(t_k) = i_k\} \\ \text{such that } \omega_1 = \sum_{l=1}^{k} i_l = j \text{ and } i_l \in \{0, 1\} \end{aligned} \tag{1}$$

where, $I(t) \in \{0, 1\}$ denotes the indicator random variable for the receiver’s state at time t. Since the state of the receiver follows the *Markovian* property, the closed form expression for $p_{i,j}$ is complex. So we present an instance for $j = 1$ and $k = 2$, as follows:

$$\begin{aligned} P_{1,2}(t_1, t_2) = Pr\{I(t_1) = 1, I(t_2) = 0\} \\ + Pr\{I(t_1) = 0, I(t_2) = 1\} \end{aligned}$$



(a) (b)

(c) (d)

Fig. 2. Illustration of catastrophic collision at four different scenarios: when multiple transmitters send packet (a). same rate and at same time instant, (b). same rate but different at time instants, (c). different rates at same time instant, and (d). different rates and at different time instant. The dotted rectangle represents the catastrophic collision window.

$$\begin{aligned}
&Pr\{I(t_1)=1, I(t_2)=0\}\\
&= Pr\{I(t_1)=1\}\ .\ Pr\{I(t_2)=0 \mid I(t_1=0\}\\
&= Pr\{I(t_1)=1\}\ .\ Pr\{I(t_2-t_1=0) \mid I(0)=1)\}\\
&= \left[\frac{\mu}{\lambda+\mu}+\frac{\lambda}{\lambda+\mu}.\exp\left[-(\lambda+\mu).(t_1)\right]\right]\\
&\quad .\left[\frac{\mu}{\lambda+\mu}-\frac{\mu}{\lambda+\mu}.\exp\left[-(\lambda+\mu).(t_2-t_1)\right]\right]
\end{aligned}$$

The similar derivation can be applied for $Pr\{I(t_1) = 0, I(t_2) = 1\}$, and can be written as follows:

$$\begin{aligned}
&Pr\{I(t_1)=0, I(t_2)=1\}\\
&= \left[\frac{\lambda}{\lambda+\mu}-\frac{\lambda}{\lambda+\mu}.\exp\left[-(\lambda+\mu).(t_1)\right]\right]\\
&\quad .\left[\frac{\mu}{\lambda+\mu}-\frac{\mu}{\lambda+\mu}.\exp\left[-(\lambda+\mu).(t_2-t_1)\right]\right]
\end{aligned}$$

Considering the random arrival of symbols from different transmitters, the conditional expectation of reception of j out of $N(T) = k$ symbols, is given as follows:

$$\begin{aligned}
R(T) &= E\left[E\left[P_{i,j}(t_1,t_2,...,t_k) \mid N(T)=k\right]\right]\\
&= \sum_{k=1}^{\infty} E\{P_{i,j}(t_1,t_2,...,t_k) \mid N(T)=k\}\\
&\quad .\exp\left[M(T)\right].\frac{M(T)^k}{k!} \qquad (2)
\end{aligned}$$

where $N(T)$ is the superposition of n independent Poisson process, where each process corresponds to the generation of information for each transmitter, and the combined average rate is $m(t) = m_1(t) + m_2(t) + ... + m_n(t)$. T represents the duration of maximum time span for the arrival of k symbols.

$$\begin{aligned}
&E\left[P_{i,j}(t_1,t_2,...,t_k) \mid N(T)=k\right]\\
&= \int ... \int_{\omega_2} P_{i,j}(t_1,t_2,...,t_k)\\
&\quad .f(t_1,t_2,...,t_k)\ dt_1\ ...\ d_k.\\
&\qquad \omega_2 \equiv 0 \le t_1 \le t_2 \le ... \le T \qquad (3)
\end{aligned}$$

Following the theorem given in Ref. [25](pp. 310) for inhomogeneous Poisson process, We have.

$$f(t_1,t_2,...,t_k) = k!\prod_{i}^{k}\frac{m(t_i)}{M(T)^k} \qquad (4)$$

Eqn. (2) is derived using Eqns. (3) and (4), and is given as follows:

$$\begin{aligned}
R(T) &= \sum_{k=1}^{\infty}\left[\int ... \int_{\omega_2} P_{i,j}(t_1,t_2,...,t_k)\right.\\
&\quad \left..\prod_{i=1}^{k} m(t_i)\ dt_1\ ...\ dt_k\right].\exp\left[-M(T)\right] \qquad (5)
\end{aligned}$$

Finally, we compute the probability of successful reception of symbols using Eqn. (6) given below:

$$P_{success} = \frac{R(T)}{1-\exp[-M(T)]} \qquad (6)$$

IV. ANALYTICAL RESULT

In our experiment, we were interested in observing the probability of successful reception of symbols when the receiver goes to "ON" and "OFF" states, an aspect that is guided by the rate parameters. The graph shown in Fig. 4 clearly informs us that the more time the receiver is in the "OFF" state, the lesser is the successful probability of reception of symbols. The reason behind this is that symbols get dropped due to the incapability of the receiver to receive — the duration for which the receiver's energy remains empty. The plot in Fig. 5 is obtained by varying the arrival rates of the transmitters. As the arrival rates of symbols increases the probability of successful reception of symbols also decreases. This is because, simultaneously more arrivals of symbols are not processed by the receiver and hence, the event of dropping numerous symbols trigger this phenomenon. The interesting fact we obtain from this plot is that the probability of successful reception remains the same for the receiver staying long in the "OFF" state even if the arrival rate is very low — it does not depend on the arrival rate.

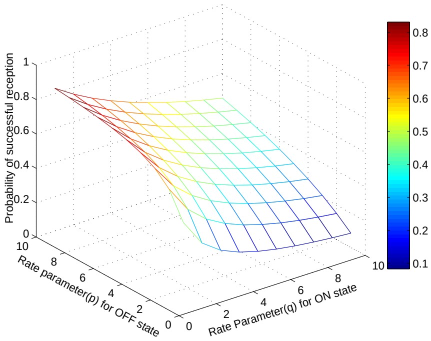


Fig. 4. Probability of successful reception of symbols for variation of rate parameters of exponential distribution at the "ON" and "OFF" states of the receiver.

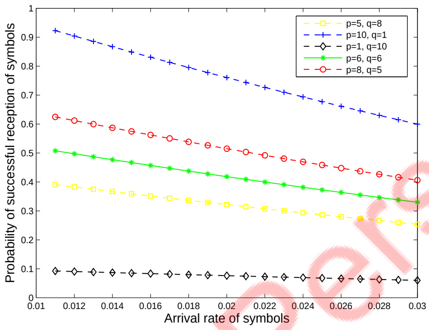


Fig. 5. Probability of successful reception of symbols for variation of arrival rate constraint to fixed rate parameters (p and q) of the exponential distribution.

V. CONCLUSIONS

Catastrophic collision, a new phenomenon in the context of WB2N, which is the result of recurrent collisions of femtosecond-long pulse symbols, transmitted by devices randomly, is analyzed in this paper. One of the major considerations in WB2N depends on successful communication between bio-nanodevices. In our present work, we analyze the severity of catastrophic collision, as it appears as a deterrent for successful communication. The main findings of our study suggest that further research on communication protocols should take into consideration of the unique behavior of the terahertz channel and the temporal energy fluctuation of bio-nanodevices.

As future work, we will investigate how catastrophic collision could be minimized in efficient manner by taking into the account of other communication metrics such as throughput, delay, and energy consumption.

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