Impact of Gateway Placement on Cancer Detection in Blood Vessels

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***Abstract*—The early detection of cancer biomarkers in blood vessels through nanosensors is crucial for timely medical intervention. These nanosensors, circulating within the blood vessels, detect biomarkers and transmit their findings to the external environment via a gateway. The strategic placement of the gateway within the human body aims to minimize the delay in the early detection of critical infections by mobile nanosensors, ultimately improving healthcare outcomes. In this work, we analyzed how the placement of the gateway influences the detection of various infection locations by nanosensors. Through a Monte Carlo simulation, we deployed 1000 nanosensors circulating in the blood vessels over a duration of 1000 seconds. The findings demonstrated that positioning the gateway at the heart significantly reduced detection time and enhanced the detection ratio, irrespective of the infection locations. This analysis underscores the importance of gateway placement in maximizing the effectiveness of the nanosensor network for detecting abnormalities across various infection locations.**

I. Introduction

In the realm of Internet of Bio-Nano-Things (IoBNT), envisioning the circulating nanosensors within the Human Circulatory System (HCS) for the timely monitoring of infection locations marks a significant leap forward. The injected nanosensors monitor the bloodstream and collect data from adjacent body regions and report their information to a gateway. The realization of IoBNT illustrates the use of gateway to forward the reported information to healthcare professionals, as depicted in Fig. 1. A reference simulation model has been proposed for communication between nanosensors and the gateway [1]. Prior works focusing on nanosensor to gateway communication illustrates the placement of gateway at different parts of human body, such as heart, wrist, hip, and ankle [2], [3]. However, in the context of serious infections, where timely monitoring and detection are critical, relying on randomly chosen gateway locations contributes to delays in the detection process.

In this context, we extend our previous work of abnormality detection [4], to analyze the strategic placement of the gateway in various locations, aiming to ensure that this placement does not compromise either the detection time or the detection ratio. To enable effective detection, the metric Age of Information (AoI) is utilized to assess the freshness of information originating from a source (here, infection location) and analyze timely updates, taking into account the constraints of the molecular communication channel [5]. By understanding average AoI and the Peak Age of Information (PAoI), we gain insights into the temporal dynamics of information flow at the receiver (here, gateway). In healthcare scenarios, especially in the dynamic environment of the circulatory system, having the most up-to-date information is crucial for prompt responses to emerging infections or abnormalities. Having information in a timely manner enables us to respond effectively to critical events. In this work, we analyze the optimal localization of the gateway and develop a methodology to evaluate the detection time and detection ratio of the abnormalities at the gateway. As nanosensors decay over the course of their mobility, we aim to analyse how this decay affects detection ratio. Consequently, to analyze the timely identification of abnormalities, we delve into the dynamics of AoI over the decay of nanosensors. Our major contributions can be summarized as follows:

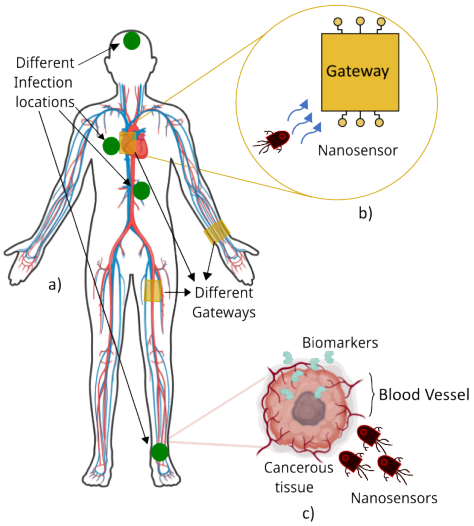

Fig. 1. Nanocommunication-based cancer biomarker detection system. a) Human circulatory system. b) Communication between nanosensors and the gateway. c) Nanosensors detecting biomarkers at the target location.

- We develop a methodology to evaluate the detection time and detection ratio of the abnormalities for optimal localization of the gateway;
- We evaluate the PAoI metric for nanosensor to gateway communication and analyze it for the decay of nanosensors over the simulation time.

II. System Model

In this section, we outline the system components of the envisaged detection system and describe the methodology to compute the detection parameters at the gateway. The model essentially includes the following components.

1) Biomarkers: These are specific molecules released by cancerous tissue, indicating potential risk. These biomarkers serve as signals for the presence of an abnormality (infection) or cancerous tissue.

2) Nanosensors: They constantly patrol the bloodstream and are designed to detect specific biomarkers that are released by infection location. When a nanosensor encounters the biomarkers, it gets activated, essentially prepared to report the detection at gateway.

3) Gateway: It is a computing device which gathers all the data reported by the nanosensors, process them, and notifies the healthcare providers about the potential risk. The nanosensors communicate with the gateway using widely acknowledged intra-body communication link, such as terahertz or ultrasonic channels [4].

Following the model in our previous work [4], we consider the nanosensors move along passively within the HCS. The nanosensors flowing through the vessels get activated upon detecting the biomarkers released by the infection location or abnormality. These traveling nanosensors report the detection of an infection when they encounter the gateway along their path. We utilize the data generated from the BloodVoyagerS (BVS) [6], which simulates the mobility of nanosensors in the bloodstream within all major vessels of the HCS. Each vessel and organ included in the simulator is assigned a distinct identifier (vesselID), the details of which can be found in our previous work [4]. The raw data from BVS provides the global position of the nanosensors randomly visiting different vessels and gateway. These nanosensors individually communicate with the gateway to report the presence of infections. The gateway processes data reported from each nanosensor n separately and then computes the detection time T_n as follows

$$T_n = t'_n - t_n, \tag{1}$$

where t_n is the time instant of the nanosensor flowing across the infection location and t'_n represents the time instant when the nanosensor travels across the gateway. To compute the detection ratio, we determine the numerator by identifying the total number of nanosensors moving in a loop through the infection location. This represents the nanosensors that successfully detected the infection. For the denominator, we identify the total number of nanosensors traveling through the loops that also enclose the gateway (further details on loops can be found in [4]).

$$\delta = \frac{\Sigma_{i \in L_i} N_i}{\Sigma_{i \in L_{i,g}} N_i}, \tag{2}$$

where N_i is the total of nanosensors flowing through the human body. L_i represents the set of loops including the infection location and $L_{i,g}$ represents the set of loops including both the infection location and gateway. To compute PAoI, we first identify AoI, which is the time instant when the first status update is received at the gateway τ_j from a particular location. It is important to note that multiple nanosensors may fetch the same status update from an infection location. However, such repeated status updates are discarded at the gateway and this redundancy does not enhance the freshness of information at the gateway. For a specific status update τ_j, we define it as the time difference between the time instant when an update is received and the time instant when it was initially generated at the infection location. The PAoI represents the maximum value of AoI, which is the time instant just before the arrival of a new status update, given as follows

$$A_j = \tau_j + g_j - g_{j-1}, \tag{3}$$

where $g_j - g_{j-1}$ is the inter-arrival time of a status update.

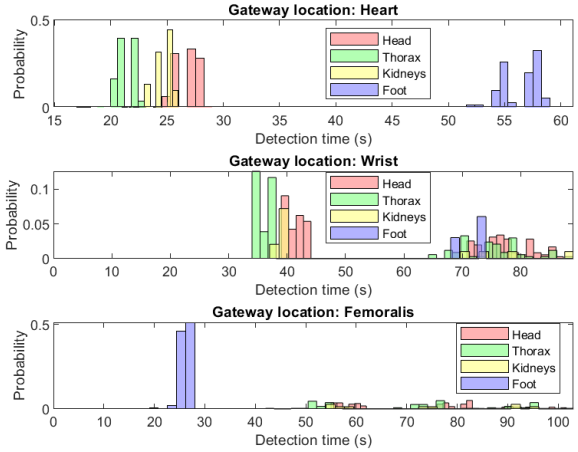

Fig. 2. Detection time for different gateway locations

III. Results and Discussion

We performed a Monte Carlo simulation with 1000 nanosensors travelling in the HCS for 1000 seconds and computed the detection time, detection ratio, and PAoI. We considered three different locations of the gateway – Heart, Left Wrist and Left Femoralis, and four different infection locations – Head, Thorax, Kidneys, and Foot. Fig. 2 depicts the normalized histogram plot for the time incurred by the nanosensors in successful detection of different infection location. The detection time is lesser when the gateway is placed at the Heart for the infections located at the upper parts of the human body. For an infection at the lowest body part, the gateway at Femoralis incurs the lowest detection time. However, in Fig. 3 we can observe that the detection ratio is more for all the infection locations when the gateway is placed at Heart as compared to Wrist. For gateway located at Femoralis, the detection ratio is negligibly higher for infection location at Foot in comparison to Head and Thorax. Thus, it can be concluded that placement of the gateway at the Heart is the optimal location.

Fig. 4 illustrates the average detection ratio with the varying rates of decay in nanosensors. We show the results for different infection location while gateway located at the Heart. The detection ratio exhibits reduced variance in scenarios with increased decay rates. This is attributed to the diminished number of samples in the system, a consequence of the decaying of nanosensors. To assess the influence of system parameters, we analyze the PAoI across varying decay rates of monitoring nanosensors in the HCS. We conducted the

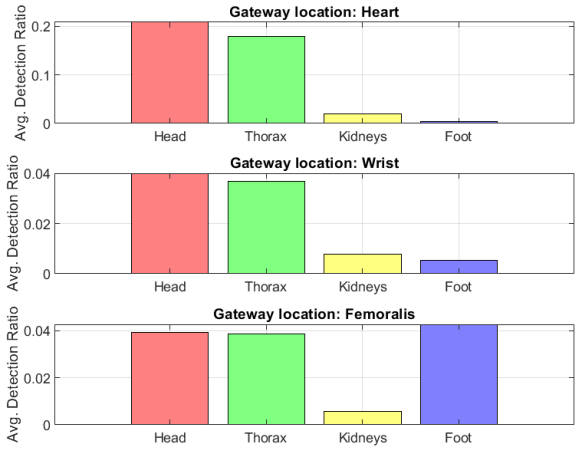

Fig. 3. Average detection ratio for different gateway locations

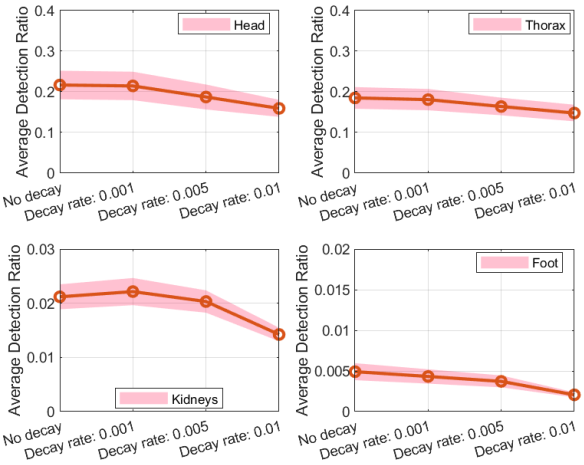

Fig. 4. Average detection ratio versus decay in nanosensors

analysis with the gateway located at heart. Fig. 5 depicts the variation of average PAoI with respect to increasing decay rates of nanosensors. We observe that the average PAoI experiences a notable increase with the rise in nanosensor decay. This suggests that as nanosensors degrade more rapidly, the time it takes for information to reach its peak freshness at the gateway also increases on average. Lower AoI means that the information about the infection location is more accurate and less prone to delays. This accuracy is crucial for precisely localizing infections within the complex network of vessels and organs. This analysis signifies that the quantity of nanosensors patrolling in the circulatory system holds significant importance. A limited number of nanosensors result in delayed transmission of infection detection status updates to the gateway, consequently increasing the PAoI.

IV. Conclusion

We addressed the issue of placing the gateway at arbitrary locations by conducting a comprehensive analysis of gateway placement, considering factors, such as detection time and detection ratio. Our findings show that the gateway placement

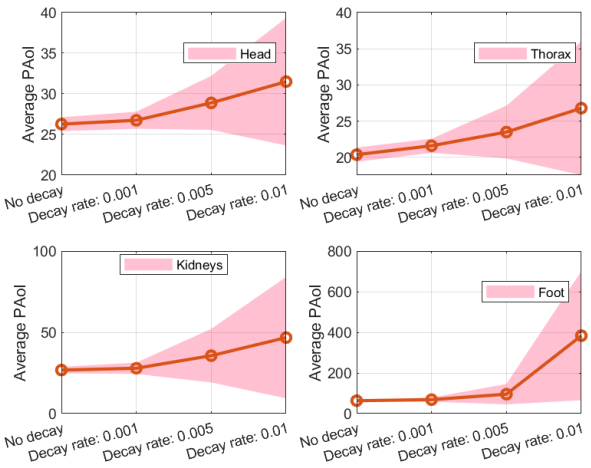

Fig. 5. Average PAoI versus decay in nanosensors

at heart enhances the efficiency of abnormality detection in the intricate network of the human body. By optimizing the precise location of the gateway, we can significantly contribute to advancing the field of healthcare technologies and improve the overall effectiveness of monitoring systems employing mobile nanosensors. The placement of the gateway indeed influences the detection time; however, finding the optimal trade-off between delay and detection rates is challenging. The best balance depends on the nature of the abnormality being detected, with some conditions allowing for a short delay while others necessitate early detection. Achieving an optimal balance is context-dependent, involving a careful consideration of the importance of timely detection against the detection ratio.

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