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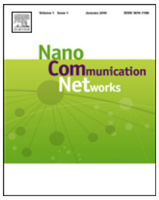

Energy requirements of error correction codes in diffusion-based molecular communication systems

Yi Lu [a], Xiayang Wang [a], Matthew D. Higgins [b,*], Adam Noel [c], Neophytos Neophytou [a], Mark. S. Leeson [a]

[a] School of Engineering, University of Warwick, Coventry, CV4 7AL, UK
[b] WMG, University of Warwick, Coventry, CV4 7AL, UK
[c] School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON K1N 6N5, Canada

HIGHLIGHTS

- A refined communication model is applied in the analysis of un-coded and coded system.
- The application of self-orthogonal convolutional codes (SOCCs) within molecular communications systems is investigated with respect to both bit error rate (BER) and energy efficiency.
- The codes are compared against both un-coded systems and one which employs Hamming codes.
- The energy budget for nano-to-nano device communication, nano-to-macro device communication and macro-to-nano device communication is investigated.
- Under each scenario, the results detail to the reader the optimum choice of code.

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ABSTRACT

Molecular Communications is a promising area with significant potential applications. To enhance the reliability of the transmission process, self-orthogonal convolutional codes (SOCCs) are proposed and investigated with respect to both bit error rate (BER) and energy efficiency. The codes are compared to both an un-coded system and one that employs Hamming codes to show that they can provide a benefit for molecular communication systems. The influence of the channel memory is also analysed in this paper. In addition, taking into account the extra energy required to implement the coding, the critical distance is investigated as another performance metric for nano-to-nano device communication, nano-to-macro device communication and macro-to-nano device communication. Considering the transmission distance and the operating BER of the designed system, the designer can determine whether the use of coding is beneficial or which code better suits the system.

1. Introduction

With the ever increasing developments in nanotechnology, the number of potential applications requiring connectivity between each of the nano-devices has risen accordingly. Furthermore, in order to establish, or improve these nano-communication systems and associated applications, knowledge about the interaction of the nano-devices with the classical network is becoming more commonly considered within the Internet of Nano Things (IoNT) [1] paradigm. One of the key applications proposed as part of this IoNT is that of intra-body health monitoring where the channel is based upon the diffusion of molecules.

An example is shown in Fig. 1 which illustrates the simplified structure of a health monitoring system that may comprise two sizes of device. A nano-sensor or nano-robot may be present, which is essentially a device whose components are all at the scale of a nanometre. For example, drug delivery mechanisms [2], or targeted surgery sensors [3]. Also present may be macro-devices which are manufactured using traditional micro-scale components, such as those found in micro-electro-mechanical systems (MEMS) [4]. These macro devices are not designed to be

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[*] Corresponding author.
E-mail addresses: Yi.Lu@warwick.ac.uk (Y. Lu), xiayang.wang@warwick.ac.uk (X. Wang), m.higgins@warwick.ac.uk (M.D. Higgins), anoel2@uottawa.ca (A. Noel), n.neophytou@warwick.ac.uk (N. Neophytou), mark.leeson@warwick.ac.uk (M.S. Leeson).

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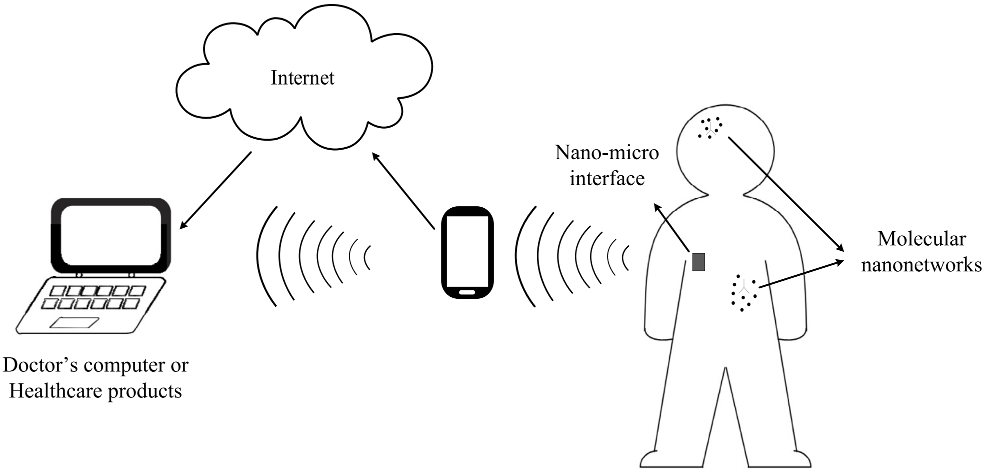

Fig. 1. A simplified health-care monitoring system design.

mobile and are most likely found on (or just under) the skin. In essence, the macro-device acts as the gateway between the nano-device and the wider network or Internet.

Already, with this simple scenario, a range of issues can be identified between the patients' nano-sensor/device and the doctor. Not only are there numerous physical layers to accommodate, but there are likely to be different requirements in the data and control aspects at each stage, some of which will be well-defined, but others will not. For example, the TCP/IP of the internet, or one of the numerous IEEE802.x Wi-Fi standards, are not up for negotiation, whilst the protocols required for the links between nano- and macro- devices, are still at the debate stage within the literature [5–9].

There will also be issues regarding the power availability. It has been claimed that the nano-devices will most likely have to work in the nW, if not pW region [10], whilst the macro-devices are essentially unconstrained in comparison. Overarching all of this are issues regarding data integrity and security which for medical applications are likely to define the level of social acceptance [11].

This paper focuses on the link between the nano-device and the nano–macro interface, where specifically, it is assumed that the link be based upon a molecular diffusion [4] process. As is true for most, if not all, communications systems, it is vital that the data transmission is both efficient and reliable. Thus, the use of Error Correction Codes (ECCs) has become an essential part in the communication system design.

The first attempt in analysing the benefits of coding techniques in a molecular communication system was presented by Leeson and Higgins in [12,13], where the Hamming codes were implemented. Crucially, the results took account of the overall complexity of the encoding and decoding process such that the amount of energy that would be required was also considered, which then allowed the determination of the critical distance [14]. Further work followed in [15] focusing on the need to introduce simple codes due to this issue of energy use. Additional codes, including High-order Hamming Codes [16], Minimum Energy Codes [17], Low Density Parity Check Codes and Reed–Muller Codes [18] have also been investigated. In each of the aforementioned investigations, code simplicity, system performance and energy requirements became the critical areas when considering the choice of coding techniques within molecular communication systems. It can also be seen that all codes were block codes.

There is another class of ECC besides block codes, known as convolutional codes. One such code is the self-orthogonal convolutional code (SOCC). A SOCC is a kind of convolutional code that has a property of being easy to implement thus satisfying one of the key design requirements of code simplicity [19,20]. Further motivation of this study is that this kind of convolutional code has been shown to have an equal, or superior performance to block codes in low cost and low complexity applications. Numerous examples can be found detailing their competitiveness in practical applications [21–24].

The proposal to introduce the use of SOCCs in molecular communication systems was first introduced by Lu et al. [25]. However, two key observations could be made about the work. Firstly, the channel model implemented could only account for ISI under the assumption that molecules were not removed from the channel after their reception, i.e. the use of a non-absorbing receiver. Secondly, the results were then limited to cover only the effects of ISI from one previous symbol. Thirdly, the work only considered nano-to-nano links which as noted above limited the overall impact of the work.

Since the original publication of [25], the community has more commonly moved to adopt a model that assumes absorbing receivers and as such, the channel model of [26] will be used herein. The use of this model is an advance to the field as no other paper on the topic of error correction codes within molecular communications currently assumes an absorbing receiver. Through using this model, this paper aims to provide a derivation of the BER for both coded and uncoded systems. This allows for this work to also be used as a guide to how the results are formed and should therefore act as a tutorial to assist the reader in applying new codes to their own specific future systems.

Next, the use of SOCCs is investigated as an candidate code, and their performance, in terms of coding gain and critical distance is evaluated against a system that is un-coded or uses Hamming codes. Finally, to enhance the impact of this investigation, making it applicable to as many elements of a system, such as the one in Fig. 1, the results are the expanded to include communications links between nano-devices and macro-devices by incorporating assumptions of their respective power budgets.

The remainder of the paper is organized as follows. Section 2 describes the communications channel model. In Section 3, the energy model of molecular communications is discussed. The theoretical and implementation aspects of Hamming codes and SOCCs are then shown in Section 4 which also provides the reader with a definitive set of equations needed to calculate the energy requirements. Section 5 then provides the numerical results, followed by the conclusions in Section 6.

2. The communications channel model

In this work, the information is transmitted from the transmitter (T_X) to the receiver (R_X) by a certain number of diffused