Advanced Receiver Designs for Bacterial Communication with Amplitude Source Addressing

Bhuvana Krishnaswamy, Raghupathy Sivakumar
School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA

ABSTRACT

In this work, we focus on the problem of *amplitude source addressing* in a multiple source single receiver bacterial communication network. *Amplitude addressing* is an addressing mechanism where the amplitude of transmitted signal is assigned as address of the source. When multiple sources collide, receiver performs interference cancellation and minimizes collision resolution error. We propose two receiver designs for an amplitude addressing system. We show that amplitude-addressing along with an optimum receiver implicitly solves the problem of medium access control.

1. INTRODUCTION

Molecular communication has been studied with focus on a single link with one transmitter and one receiver. In this work, we focus on a multiple source single receiver topology as shown in Figure 1. Such a topology can be most commonly observed in sensor networks where multiple sensors communicate to a single receiver. [4] considers this topology and proposes amplitude source addressing that assigns unique amplitudes to each source which is then used as its local address. [4] uses a simple receiver that decodes one of the many possible inputs randomly on receiving a collided signal. In this work, we focus on advanced receiver designs robust to varying input distributions and increasing number of sources.

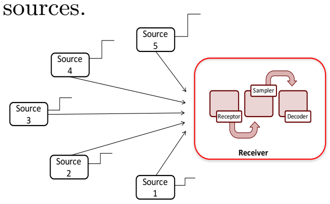

Figure 1: Network Setup

In this paper, we make the following contributions: First, we propose *Probabilistic Receiver*, a mathematically simple receiver design that decodes using apriori probabilities. Second, we propose *Deterministic Receiver*, an advanced receiver design that maximizes network throughput and minimizes decoding complexity.

2. AMPLITUDE SOURCE ADDRESSING

An *amplitude source addressing* mechanism assigns each source a unique amplitude a_i, which serves as the address of that source. Each source uses a_i to transmit information using a given modulation scheme. In this work, we assume that all sources use On-Off-Keying to transmit bits i.e., a rectangular pulse of "T" time units with a concentration equal to the amplitude assigned [3]. On receiving a signal with amplitude y, the receiver resolves the sources based on y. If multiple sources transmit simultaneously, signals collide in the channel and receiver receives the sum of the amplitudes being transmitted . If the number of partitions of this received amplitude y is *1* ,i.e., the number of ways in which a_{is} can be added to reach a sum y is *1*, then all users that were transmitting in this time slot can be resolved without any error. If the number of partitions of y is ≥ 2, average error in resolving all sources is ≥ 0. The two main factors affecting the resolution of source addresses on receiving a signal are, 1. Amplitudes assigned and 2. Receiver design. The impact of amplitude assignment was discussed in detail in [4]. Receiver design determines the accuracy of source address resolution on receiving a signal given the amplitudes. When the number of partitions is ≥ 2, the receiver can choose from multiple configurations that sum to received signal. In this work, we propose two receiver designs using the principles of Maximum Aposteriori detection viz., 1. Probabilistic receiver 2. Deterministic receiver. We make the following assumptions about the network in the design and evaluation of the receiver designs. R_{max} is the maximum amplitude receiver can uniquely identify i.e., receiver can decode amplitudes $\{1, 2, 3, .., R_{max}\}$ in a network with N sources. Each source is assigned a distinct amplitude i.e., $N \leq R_{max}$. We assume that the sources are time synchronized and are backlogged i.e., they always have data to transmit. p_t and $1 - p_t$ are the probability of each source transmitting bit 1 and bit 0 respectively. The probability of each configuration occurring (transmitted) in the channel depends on the probability of a source sending bit 1 and bit 0 and number of 0s and 1s in the configuration. Therefore, probability of all sources transmitting zeros is $(1 - p_t)^N$.

3. RECEIVER DESIGNS

3.1 Probabilistic Receiver(PR)

[2] proves that a MAP(Maximum a-posteriori) decoder is an optimum decoder that minimizes symbol error in a discrete memoryless channel. We apply the principle of MAP receiver in designing PR that chooses one of the partitions that maximizes the conditional probability PR. PR chooses one of the many partitions of the received amplitude using a-priori probability of occurrence of each partition of the amplitude. Therefore,the probability of decoding a signal is proportional to the probability of its occurrence. A mathematical description of probabilistic receiver is used to design a simpler receiver later in the paper. Let m_k be the bit transmitted by user u_k in a given time slot and $\hat{m_k}$ be the bit receiver decodes on receiving the signal y. The decoding is successful for user u_k if $m_k = \hat{m_k}$. Let Y be a random variable that represents the received amplitude. Thus, probability of success for user u_k on receiving an amplitude y is $\Pr(\hat{m_k} = m_k \mid Y = y)$. Note that m_k is the bit transmitted by user u_k and $m_k \in \{0, 1\}$. Therefore, probability of success for user u_k is,

$$\Pr(\hat{m_k} = m_k \mid Y = y) = \sum_{i \in \{0,1\}} \Pr(\hat{m_k} = m_k, m_k = i \mid Y = y) \quad (1)$$

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Let $\Pr(Y = y) = p_y$ where p_y is the sum of probabilities of configurations with magnitude y. PR chooses a partition with a probability equal to its apriori probability. Thus, on receiving an amplitude y given $m_k = 1$, user u_k is successful if receiver chooses any one of the partitions such that $m_k = 1 \& Y = y$. Using Bayes' rule we derive that,

$$\Pr(\hat{m_k} = m_k \mid m_k = 0, Y = y) = p_{y^0} = p_y - p_{y^1}$$

Substituting the above equations,

$$\Pr(\hat{m_k} = m_k \mid Y = y) = \frac{({p_y}^1)^2}{p_y} + \frac{(p_y - {p_y}^1)^2}{p_y}$$

Using the above probability of success, we derive the average network throughput when using a probabilistic receiver.

$$\text{Average network throughput} = \frac{\text{Expected Number of successes}}{\text{Time per slot}} \quad (2)$$

Since all users use the same time period and are assumed to be time synchronized, expected(average) number of successful users is the only variable in calculating average network throughput. The following equations are used to calculate expected number of successes.

$$\mathbb{E}(\text{successes} \mid Y = y) \leq N * \max_{1 \leq k \leq N} \Pr(\hat{m_k} = m_k \mid Y = y)$$

${p_y}^1 \leq p_y$. When the equality does not hold we can write ${p_y}^1 = r * p_y$ where $r < 1$. Substituting in the expected number of successes,

$$\mathbb{E}(\text{successes} \mid Y = y) \leq N * \max_{1 \leq k \leq N} p_y * (1 - 2r + 2r^2) \quad (3)$$

For each signal received, PR chooses one of the partitions. For an integer sequence, the number of partitions increases exponentially [1]. Thus, on receiving a signal, the receiver goes through the partitions of integers contributing $\mathcal{O}(e^N)$ to the decoding time complexity. This is repeated for each signal received and the overall time complexity is $\mathcal{O}(e^N |Z|)$ where $|Z|$ is the number of received signals.

3.2 Deterministic Receiver(DR)

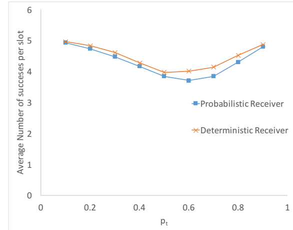
As derived in equation 3, number of successes is a function of p_y, the probability of receiving an amplitude y and r, the ratio of probability of a source transmitting bit 1 given y was received to the probability of receiving amplitude y. The equation $1 - 2r + 2r^2$ is a parabola with r as x-axis which reaches its maximum value of 1 at $r = 0$ and $r = 1$ and a minimum of 0.5 at $r = 0.5$ and is always greater than or equal to *max(1,1-r* thus proving that the throughput performance of DR is better than that of PR

Probability of success in equation 3 was derived by applying principles of MAP receiver to choose a partition. To reduce the complexity of the receiver, we propose DR that chooses a pre-determined configuration on receiving a signal. This configuration is determined on a per-user basis. The most likely bit transmitted by each source on receiving a signal is estimated from apriori probabilities. The vector of bits thus estimated is the configuration chosen on receiving a signal. DR maximizes the conditional probability of user u_k transmitting a bit given the received signal y. The maximization is performed apriori and hence the time complexity is $\mathcal{O}(1)$ i.e., constant time with a one-time estimation of partitions of all received amplitudes. To study the performance of DR, we use the same parameters as that of PR. DR can be mathematically described as,

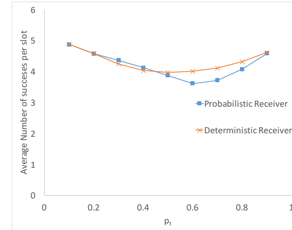
$$\mathbb{E}(\text{successes} \mid Y = y) \leq N * \max_{1 \leq k \leq N} p_y \max(r, 1 - r)$$

4. PERFORMANCE EVALUATION

We built NS_{BC} (Network Simulator - Bacterial Communication), a python based simulator, to evaluate the performance of bacterial communication network. Channel is assumed to be noise free i.e., zero channel noise and hence zero modulation and zero sampling error. Each data point in the results are averaged over 100 simulations with each source transmitting 1000 bits. We evaluate the performance of two receiver designs proposed in Sections 3 and **??**. [4] presented an amplitude assignment algorithm to choose an optimum addressing sequence. Figure 2(a) shows the throughput performance of DR and PR that uses amplitude sequence proposed in [4] for $R_{max} = 15, N = 5$ for different values of p_t. At small values of N, the improvement in performance is on an average 3.6%. As the number of sources increases, the improvement in performance also increases. At N=10, this increases to 10.62% with a maximum of 17% at $p_t = 0.6$. Amplitude allocation algorithm presented in [4] relies on the value of p_t in designing the sequence and is also used by the receiver to decode. When the decoder cannot determine p_t, it assumes bits 1 and 0 are equiprobable and uses $p_t = 0.5$ to decode. We evaluate the performance of both the receivers when they are unaware of input p_t. Figure 2(b) compares performance of the receivers when they decode using $p_t = 0.5$. Average number of successes using DR does not decrease significantly. Load unaware DR performance on an average is 95% of load aware DR while that of pR is 88%. Also, performance of load unaware PR decreases for $p_t \geq 0.5$. Therefore DR does not affect the throughput performance when p_t changes. The receiver used in [4] is the same as load unaware PR. Thus, DR outperforms the receiver design in [4] by 8% at $R_{max} = 15, N = 5$ and 25% at $R_{max} = 15, N = 10$. It can be observed that the performance of receiver in [4] (load unaware PR) drops significantly with increase in number of sources.



(a) Load aware receiver $N = 5$ and $R_{max} = 15$



(b) Load unaware receiver $N = 5$ and $R_{max} = 15$

5. FUTURE WORK AND CONCLUSIONS

In this work, we proposed two receiver designs that minimizes the collision resolution error at the receiver in a multiple source single receiver bacterial communication network. We proposed a receiver design with reduced decoding time and space complexity without affecting accuracy. Though the proposed receiver design improve network throughput, there are other problems we consider for future work like, 1. Experimental verification of source addressing mechanism using bacterial transceivers 2. Channel errors : In this work, we assumed that channel is ideal and does not add any noise tot he amplitudes transmitted. Performance and analysis of receiver in the presence of channel error must be analysed.

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