Application Layer Coding for Delay and Feedback-Constrainted Scenarios

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by

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CERTIFICATE

This is to certify that the thesis entitled **Application Layer Coding for Delay and Feedback-Constrainted Scenarios**, submitted by **Vatsalya Chaubey (17EC01044)** to Indian Institute of Technology Bhubaneswar, is a record of bonafide research work under my supervision and the report is submitted for end semester evaluation of the B.Tech project.

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DECLARATION

I certify that

a. the work contained in the thesis is original and has been done by myself under the general supervision of my supervisor.

b. the work has not been submitted to any other institute for any degree or diploma.

c. I have followed the guidelines provided by the institute in writing the thesis.

d. I have conformed to the norms and guidelines given in the ethical code of conduct of the institute.

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Vatsalya Chaubey

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Vatsalya Chaubey

Abstract

Application layer in a communication network is an abstraction layer that provides a set of shared protocols and interfaces between various hosts for information transfer. It is the topmost layer in various communication models like TCP/IP and OSI and masks the underlying mechanisms and allow for communication between various applications in different hosts. Application layer codes ensure that the communication between hosts is reliable with minimum number of data packets lost in transmission. In this work we present a application layer coding scheme which utilizes intermittent feedback and can be used for delay and energy constraint applications. Such a scheme could be widely used for control operations in wireless sensor networks where a number of sensors transmit data to a common gateway for analysis and decision making purposes.

Contents

List of Symbols

$\begin{pmatrix} k \\ l \end{pmatrix}$	Binomial coefficient
s_i	Information symbol number i
$\mathbf{p}_i$	Packet number i
b	Maximum number of symbols a packet can carry
$\mathbf{q}_i[k]$	k-th symbol in payload $\mathbf{p}_i$, $1 \leq k \leq b$
u	Sequence number of the oldest undelivered packet
β	Number of unexpired packets undelivered
$c_d(\mathbf{v})$	A coded symbol produced coding XORing d random symbols from the set $\mathbf{v}$
$c_D(\mathbf{v})$	A coded symbol produced coding XORing D random symbols from the set $\mathbf{v}$, where D is a uniform random variable
$\mathbf{v}[k]$	k-th entry of vector $\mathbf{v}$
$\mathbf{v} \backslash \{x\}$	set of all entries of $\mathbf{v}$ except x

Chapter 1

Introduction

This chapter provides a brief summary of the Application layer which forms an integral part of the TCP/IP and OSI networks models. This chapter also discusses the need of application layer coding and basic description of some schemes already in use. In the proceeding sections, we also discuss our use case along with a description of a previous works already done in this area.

1.1 Application Layer

The Transmission Control Protocol (TCP) and the Internet Protocol (IP) forms the backbone of today's internet and other data communication methods. They are collection of protocols that defines how the data is to be packetized, framed, addressed, transmitted, routed and received. All of these various functions are abstracted through various layers each having a specific function. The TCP/IP protocol suite has five layers and application layer is one of them.

Application Layer is present at the top of the TCP/IP and OSI models. It is through this layer that a user interacts with the system. It also provides services and interfaces which ensures that an application can communicate with any other application on the

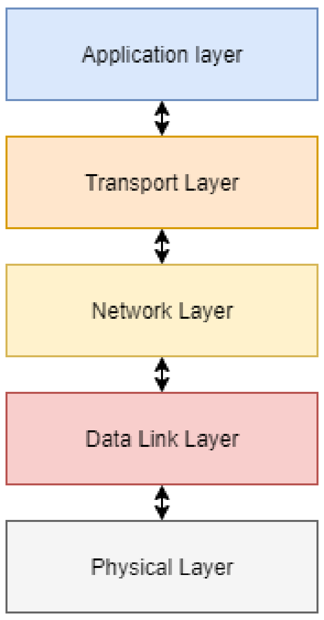


Figure 1.1: Various layers of the TCP/IP protocol. The Application Layer sits at the top

same network. Though the name states "Application Layer", it should not be thought of a software application rather it is a component of the application which allows it to communicate to other applications on the network through the various lower layers of TCP/IP protocol. It serves to abstract the messy inner steps involved with the lower layers during data communication or transfer. Figure 1.1 shows the various layers involved in the TCP/IP protocol. The application layer protocols provides various functions:

- **Identification of Communicating Nodes:** The application layer decides the availability of a node for an application with data to transmit.
- **Resource availability:** It also decides whether the amount of network resources required for any communication are available.
- **Synchronization:** It make sures that applications communicating with each other are in sync.

1.2 Problem Formulation and Motivation

Many wireless networks operate in certain in frequency band where they are subjected to various duty cycle constraints. Moreover, the current trend of building connected devices or systems has made it necessary for using many sensor nodes transmitting data to a receiver for further processing and decision making. So these duty cycle constraints limit the ability of the receiver to transmit feedback about the reception of packets back to the sensors. In a similar fashion, the sensor nodes themselves can only make a limited number of retransmissions for erasure correction. Now, the task of designing an efficient application layer coding scheme which can used in the above scenario becomes challenging, but, if the use cases are delay sensitive then it becomes further complicated. In such a scenario, one data packet generated at the source is of value to receiver only for a certain time frame and after passage of that threshold it becomes useless. Examples of such networks can be found in sensor networks in industries which monitor and control various processes in a plant and where most decisions are made in real-time.

In this thesis, the focus is on a duty cycle and feedback constrained delay sensitive multipoint to point communication. The work is based on creating modifications to an existing coding technique [1]. In our use case, the data generated is valid for a fixed time interval, after which its importance cease to exist. All transmission made by the sensor node can be a uncoded packet (pure information packet or message) or a coded message (a data packet formed by linear combination of two or more messages). Since most sensor are low-powered devices we aim to develop a coding scheme which is computationally cheap and avoids coding packets unless absolutely necessary. The feedback structure of the system is also designed in a way such that maximum information about the receiver state can be transmitted back to the receiver. The design also makes sure that even if feedback is missing coding is done effectively to ensure better packet reception. We limit our design to GF(2) where coding is done by simply XORing two symbols to avoid complex coding schemes in higher order fields.

1.3 Literature Survey

LT codes [2] and Raptor Codes [3] have been used widely due to their strong erasure correction. They operate over a large set of symbols which translates to higher decoding delays. This delay makes them useless for delay-constraints applications. [4] attempts a coding scheme with smaller blocks of information symbols. They investigate the effectiveness of their approach for networks where a number of senders transmits to a single receiver over an erasure channel but with perfect feedback. They account for the delay constraints but fail to acknowledge the duty cycle constraint in our case. Later, [5] introduced a new network adaptive coding scheme for low latency communication. They aimed at reducing both random and burst erasures by coding in a higher order field, namely GF(256). Since, their work focused on streaming applications they could afford coding in such high order fields, but in our resource constraint use case coding in such higher order fields would drastically increase the computational complexity, which would make the sensors power hungry and energy inefficient. Some of the above mentioned problems were addressed in [6], where they design a coding scheme for LoRaWAN which provides better packet reception and reliability against burst and random errors. The system is designed in complete absence of feedback, which proves to be a vital resource if used efficiently.

The authors of [1] introduce two coding schemes—*Windowed Coding and Selective Coding* for our use cases. Both of the schemes make use of available intermittent feedback along with a unique packet structure and coding scheme. They intelligent decide when to code and how many symbols are to be coded. They also provide steps to perform when feedback is unavailable. This current work is heavily based on the *Windowed Coding* scheme making modifications to it to remove the implicit shortcomings of that approach. The *Windowed Coding* scheme is described in detail in Chapter 2.

Chapter 2

Windowed Coding

In this chapter, we discuss the *Windowed Coding* scheme introduced in [1] on which this work is based upon.

2.1 General Packet and Network Structure

The sender generates a information symbol s_i at the current time instant, i. Let us assume, δ_{max} to be the maximum delay tolerance. So, all the symbols generated before the time instant $i - \delta_{max}$ are of no use to the receiver. Multiple symbols are transmitted together as a single packet, instead of transmitting each symbol as seperate packet as done in [4, 5]. This is done to utilize the packet structure of LoRa, where the packet duration remains same data size of 1 byte through 4 byte [7], allowing to maintain the energy and duty cycle restrictions.

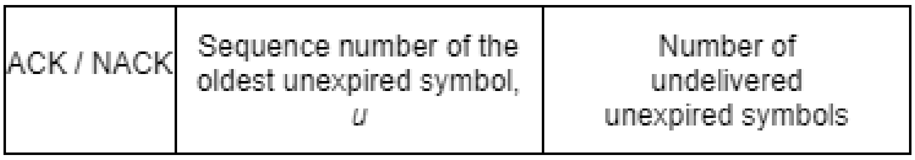
Multiple information symbols can be coded together and transmitted to increase redundancy. A *coded* message is formed by XORing d information symbols as in Eq. 2.1. d is known as the coding degree. A coded packet can be decoded at the receiver if $d - 1$ packets are already received as in Eq. 2.2. So, a coded packet can be used to decode at max one symbol, but the advantage of coding is that the retrieved symbol can be any one of the d symbols.

$$c_d = s_1 \oplus s_2 .... \oplus s_d \tag{2.1}$$

$$s_d = c_d \oplus s_1 .... \oplus s_{d-1} \tag{2.2}$$

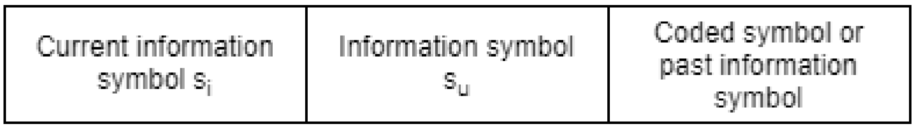
A symbol can be successfully received at the receiver if it is delivered in its raw state or if it can be decoded from a coded packet.

The size of a packet, b is the number of symbols (coded or uncoded) that can be incorporated in a packet. If the maximum size of packet is l_p bits, decided by the duty cycle constraints, and each symbol is l_s bits then the size $b = l_p/l_s$. The first symbol in the packet is always the current symbol i.e the symbol at time i. The symbols following it may be coded or uncoded.



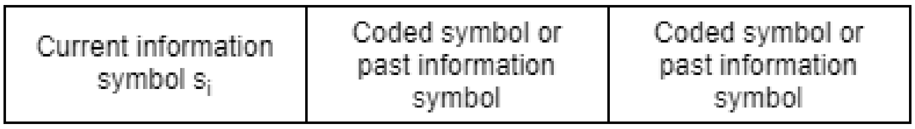
ACK / NACK	Sequence number of the oldest unexpired symbol, u	Number of undelivered unexpired symbols

Figure 2.1: Structure of the feedback packet



Current information symbol s_i	Information symbol s_u	Coded symbol or past information symbol

Figure 2.2: Packet structure of size 3 when feedback has been received for the previous packet



Current information symbol s_i	Coded symbol or past information symbol	Coded symbol or past information symbol

Figure 2.3: Packet structure of size 3 when feedback has not been received for the previous packet

The sender transmit a packet using one of the structures as shown in Fig. 2.2 and Fig. 2.3. The structure of the packet is decided by the coding algorithm described in the next section. The transmissions take place over a erasure channel. The paper [1] describes its results for Bernouli, Gilbert-Elliot and LoRa channels. Every sender may receive a feedback from the receiver with a probability of $p_{feedback}$. The structure of feedback is shown in Fig. 2.1 where the first bit ACK/NACK provides acknowledgement whether the current symbol, s_i was delivered or not. It is followed by two data symbols which contain the sequence number, u of the oldest unexpired symbol and the total number of undelivered unexpired symbols, β. If all the packets up till the current packet has been received, the feedback will contain $u = i + 1$ and $\beta = 0$

2.2 Coding Scheme

The sender at time instant i produces an information symbol s_i. To form the packet $\mathbf{p}_i$, the first entry would be the current packet s_i. Now it needs to choose how to prepare package $\mathbf{p}_i$. This decision is made based on whether feedback was received for the previous packet $\mathbf{p}_{i-1}$.

1. *Feedback for the packet* $\mathbf{p}_{i-1}$ *was received*

   The feedback will inform the sender the oldest undelivered symbol, u and the number of undelivered unexpired symbols, β in the range $(i - u, i)$. Then the symbols of the interest to the receiver from a set $\mathbf{w}_i = \{s_u, s_{u+1}, ..., s_{i-1}\}$. The remaining $b - 1$ spaces are filled based on the below conditions:

   (a) $u = i$: This would mean that all the symbols upto the current symbol have been received by the receiver and nothing extra needs to be sent.

   (b) $u < i, i - u \leq b - 1, \beta \geq 1$: This would mean that all the $i - u$ symbols of interest can fit inside the remaining $b - 1$ space of the payload $\mathbf{p}_i$. So all the symbols in $\mathbf{w}_i$ are appended to the payload $\mathbf{p}_i$.

   (c) $u < i, i - u > b - 1, 1 < \beta = i - u$: This would mean that all the $i - u$

symbols are missing and there is not enough space in the payload $\mathbf{p}_i$ to include everything. Since all the symbols in $\mathbf{w}_i$ are missing the first $b-1$ packets are appended to the payload because they are the symbols that will lose their relevance first as compared to others.

(d) $u < i, i-u > b-1, 1 < \beta < i-u$: Here, not all symbols in $\mathbf{w}_i$ are missing, but what symbols are missing is unknown, except for s_u. Only the number of missing symbols is known. It is only in this case that coding is performed. So, first the known missing symbol s_u is appended to the packet $\mathbf{p}_i$. Now we have $b-2$ free spaces and $\beta-1$ missing symbols. So the remaining $b-2$ symbols in the payload are coded symbols generated by random linear combination of d elements from the set $\mathbf{w}_i \backslash \{s_u\}$. The degree is chosen as

$$d = \underset{d'}{\operatorname{argmax}} \frac{\binom{\beta-1}{1} * \binom{i-u-\beta}{d'-1}}{\binom{i-u}{d'}} \tag{2.3}$$

The above equation aims to choose a degree d which maximizes the probability of decoding of one packet at the receiver. Eq 2.3 is a crude estimate of the decoding success probability. Recall, that a symbol can be decoded if $d-1$ out of the d symbols are already received. So in Eq. 2.3, the number of ways 1 symbol from the $\beta-1$ missing symbols and the other $d'-1$ symbols from $i-u-\beta$ already received symbols can be chosen is calculated. To find the probability this number is divided by the total number of ways to choose d' symbols from $i-u$ symbols.

2. *Feedback for the packet* $\mathbf{p}_{i-1}$ *was not received*

If the feedback for the previous packet is not received the oldest undelivered symbol at the moment is unknown. So a set is defined as $\mathbf{b}_i = \{s_{i-1}, s_{i-2}, ..., s_{i-z}\}$ where $z = min(i-u_l, i-u_{max})$, u_l is the oldest undelivered sequence in the most recent feedback and $u_{max} = i - \delta_{max}$, the oldest unexpired information symbol at the current instant, i. This scenario can also be decomposed into similar cases:

(a) $z \leq b-1$: The entire vector $\mathbf{b}_i$ can be included in the payload $\mathbf{p}_i$ after the current symbol s_i.

(b) $z > b - 1$: This is similar to the case (d) in the feedback case. Here, again the missing symbols are unknown and not all symbols of interest can be incorporated in the payload. Coding of symbols is again employed here but since no other information about the state of the receiver is known, it is assumed that all symbols in the $\mathbf{b}_i$ are equally likely to be missing. So, coded symbols are generated by XORing D symbols from $\mathbf{b}_i$, where D is a uniform random variable between $[1, z]$.

2.3 Problems with the scheme

Though this scheme perform really well in practice, there are a few important shortcomings which need to be considered. The packet reception rate is a order of magnitude better when compared against two baselines—repetition redundancy and blind coding scheme. The scheme was evaluated on three erasure channels (Bernouli, Gilbert-Elliot, LoRa) against these baselines. More detailed results can be found in the paper [1]. Here, we focus more on three problems of this scheme and in the next chapter we will describe the steps taken to mitigate them.

2.3.1 Degree Selection when coding

The degree selection equation (Eq. 2.3) is computationally very intensive. As the delay tolerance δ_{max} will increase the value of d' will increase thus the number of times the $\binom{n}{k}$ operation needs to be done to calculate a single value of d will also increase. The complexity of one $\binom{n}{k}$ operation is approximately $O(min(n^k, n^{n-k}))$ so the complexity of selecting the degree once is approximately

$$O\left(\sum_{d'=1}^{d'=i-u-\beta+1} (i-u-\beta)^{d'-1} * (i-u)^{d'}\right)$$

when we only consider the upper bound.

This is unfathomably complex for a low power sensor node to calculate for every transmission. If such a computationally intensive equation is used to calculate the degree most of the battery of the sensor would be consumed in calculating this. One way to avoid this problem which the authors of [1] suggest is using a table of values in memory. This approach is feasible when the delay tolerance δ_{max} is low because the space complexity of this approach is $O\left(\delta_{max}^2\right)$. For the applications for which this method was first created this condition is usually met. But, in this work we want to do away of this requirement of low δ_{max} and make a more general coding scheme.

One more issue with the Eq. 2.3 is that it is only a crude estimate of successful decode probability and is only valid if the packet contains only one coded packet. If a packet contains more than one coded packet this estimate would further drift away from the actual way. To circumvent this, a joint optimization of degree should be done which was not done in [1] to avoid further complexity.

2.3.2 Feedback

The structure of the feedback packet is shown in the Fig. 2.1. Let us suppose our $\delta_{max} = 16$, which is a fairly common value in an industrial setting and the number of symbols we need to transmit is $10,000$. Then the number of bits required by our feedback would be $1 + 14 + 14 = 29$. One bit for acknowledgement, 14 bits each to represent the oldest undelivered sequence number and number of undelivered symbols. This approach is not very efficient. Even using 29 bits or more practically 32 bits, we could only know about the state of one symbol with surety i.e. s_u and just a cumulative estimate of the state of other symbols. In a way, the feedback is under utilized and more useful information can be packed in it.

2.3.3 No-feedback Coding Degree

The coding degree chosen when there is no feedback is D, which is a uniform random variable between $[1, z]$. The idea behind this is the assumption that all symbols are equally likely to be missing, which is actually not the case. Moreover, in our experiments, choosing this degree randomly underperformed when compared to a fixed degree. In our case, we could get the best performance when this degree was fixed at 2. This calls to question the theoretical reasoning behind this approach. Further study is needed to get to the actual reason behind this and come up with better methods to choose this degree.

Chapter 3

Improved Windowed Coding

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3.1 Title of Section

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3.1.1 Title of Subsection

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Appendix A

Title of Appendix

xxxxxx xxxxxx.

$$y = \alpha\, x + n \tag{A.1}$$

Publications

Journal Publications

1.
2.
3.

Conference Publication

1.
2.

Bibliography

[1] S. S. Borkotoky, U. Schilcher, and C. Raffelsberger, “Application-layer coding with intermittent feedback under delay and duty-cycle constraints,” in *ICC 2020 - 2020 IEEE International Conference on Communications (ICC)*, 2020, pp. 1–6.

[2] M. Luby, “Lt codes,” in *The 43rd Annual IEEE Symposium on Foundations of Computer Science, 2002. Proceedings.*, 2002, pp. 271–280.

[3] A. Shokrollahi, “Raptor codes,” *IEEE Transactions on Information Theory*, vol. 52, no. 6, pp. 2551–2567, 2006.

[4] E. Drinea, L. Keller, and C. Fragouli, “Real-time delay with network coding and feedback,” *Physical Communication*, vol. 6, pp. 100 – 113, 2013.

[5] S. L. Fong, S. Emara, B. Li, A. Khisti, W.-T. Tan, X. Zhu, and J. Apostolopoulos, “Low-latency network-adaptive error control for interactive streaming,” in *Proceedings of the 27th ACM International Conference on Multimedia.* Association for Computing Machinery, 2019, p. 438–446.

[6] P. J. Marcelis, V. S. Rao, and R. V. Prasad, “Dare: Data recovery through application layer coding for lorawan,” in *2017 IEEE/ACM Second International Conference on Internet-of-Things Design and Implementation (IoTDI)*, 2017, pp. 97–108.

[7] “Sx1272/3/6/7/8: Lora modem designer’s guide,” *ANI200.13 Semtech Corporation*, 2013.