Further Analysis Of A Framework To Analyze Network Performance Based On Information Quality

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Abstract

In [1], Geng and Li presented a framework to analyze network performance based on information quality. In that paper, the authors based their framework on the flow of information from a Base Station (BS) to clients. The theory they established can, and needs, to be extended to accommodate for the flow of information from the clients to the BS. In this work, we use that framework and study the case of client to BS data transmission. Our work closely parallels the work of Geng and Li, we use the same notation and liberally reference their work.

Keywords: Information Theory, Information Quality, Network Protocols, Network Performance

1. INTRODUCTION

The major contribution of Geng and Li's work was a framework that introduced information quality (IQ) as an additional attribute of information and further showed that information quality has an effect on network performance parameters, particularly system throughput. IQ reflects the degree of importance of information to the target network performance metric. The authors apply IQ to the quantitative analysis and design of network protocols.

To quantitatively measure the information efficiency (IE) of network protocols, the authors also present information efficiency and provide an approach to improve the information efficiency of protocols. Information efficiency (IE) is defined as improvement of a performance metric per bit od information as a metric as a metric of IE of network protocols [1] In their work, they study the effects of IQ and IE on network performance and show that using both IQ and IE the performance of a network can be improved. The authors base their analysis on the flow of information from a base station BS to a group of clients. In this work, we apply the concepts of IQ and IE to the analysis of the flow of information from a group of clients to the base station BS. Our results are the same as the authors and thus provides further validation to their framework.

2. PRELIMINARIES

The disciplines of information theory and networking have promised interesting connections and has received a great deal of attention from researches in both fields. One of the important early contributions by information theory was in the area of routing. Gallagher [2] provided an information theoretical analysis of minimum delay routing in packet-switched, store-and-forward networks. There have also been information theoretical analysis of multi-access communication [3], timing channel [4] and others. A summarization of this early work appears in a survey paper [5].Network information theory [6] deals with information capacity in multi-hop wireless networks and focuses on coding and channel information.

Another very active research topic is network coding [7], a research field of information theory and coding theory. Network coding is an approach derived from information theory. In [8], Chiang, et al, attempt to develop a uniform framework for network protocols.

3. FRAMEWORK AND DETAILS

3.1 Information Quality

The material in this section repeats much of the material in [1] to provide the proper background for our analysis.

IQ of information source x_i is defined using partial derivatives of the performance metric in the direction of x_i as:

$$\mathrm{Qual}(x_i) = \frac{\partial U(\,Q(\,X^{+}\,)\,)}{\partial x_i} \qquad (1)$$

where $X^{+} = \{\, x_1,\ x_2,\ .\ .\ .\ x_n\}$ represents information sources used by protocol Q and U(Q) is the performance of Q using information X^{+}.

The author's also define the idea of effective information quantity as:

$$I_{eff}(\,x_i\,) = I(\,x_i\,) \times \mathrm{Qual}(\,x_i\,) \qquad (2)$$

By multiplying information quantity by quality, where $I(\,x_i\,)$ is the quantity of information source x_i.

Effective information quality is really the original information weighted by the quality of the information. This particular parameter describes the effectiveness of the amount of information on the improvement in performance.

3.2 Fundamental Principles

The following theorems are proven in [1]. They are repeated here without proof.

Theorem 3.1: Marginal information change drives performance variation.

Comments: Given a performance metric U that is to be maximized, $Z = \{z_1,\ z_2,\ .\ .\ .\ z_N\}$ the set of information sources used by Q and x an additional source, then

$$U(\,Q(\,Z, x)\,) \geq U(\,Q(\,Z\,)\,) \qquad (3)$$

which means that additional information cannot increase uncertainty.

This result is because, with the current information, any additional information cannot increase uncertainty. If the added information is favorable, it can be used to enhance performance. If the added information is not favorable, it can simply be discarded.

Similarly,

$$U(\,Q\,(Z_{-i}\,)\,) \leq U(\,Q(\,Z\,)\,) \qquad (4)$$

Where Z_{-I} means that source Z_i is removed from the set.

*Theorem 3.2:*Increasing total information quantity does not necessarily mean better performance.

Comments: Even though

$$I(\,Z\,) > I(\,Y\,) \qquad (5)$$

does not mean

$$U(Q(Z)) > U(Q(Y)) \qquad (6)$$

Theorem 3.3: Information should be utilized as directly as possible to achieve better system performance.

Comments: Given the system performance function U, and available information sources X and Y and the relationship X -> Y -> U exists, which means Y is a more direct information source. Then, according to [9]

$$I(Y; U) \geq I(X: U) \qquad (7)$$

and further

$$U(Q(Y)) \geq U(Q(X)) \qquad (8)$$

This means that indirect information from source X reveals less about performance, U, than direct information from source Y. The system senses less uncertainty from X than from Y and consequently performs better.

Theorem 3.4: Performance variations due to marginal change of information of different qualities will differ.

Comment: Using higher quality information helps increase performance more effectively than using information of lower quality.

Theorem 3.5: Using different information jointly is at least as good as using them individually.

Comment: Given a performance function $U = U_1 + U_2$ and information source x with two sub-information sources x_1 and x_2

$$U_1(Q(x_1, x_2) \geq U_1(Q (x_1))$$

$$U_2(Q (x_1, x_2) \geq U_2(Q (x_2)) \qquad (9)$$

Then

$$U_1(Q(x_1, x_2) + U_2(Q(x_1) \geq U_1(Q(x_1)) + U_2(Q (x_2)) \qquad (10)$$

The performance, U, may not be the sum of U_1 and U_2. However, if we want to improve performance, using information jointly contributes more to improving performance using information singly.

3.3 Information Efficiency Of Network Protocols

In [1], the authors define Information Efficiency (IE) as the improvement of a performance metric per bit of information as a metric of information efficiency of protocols:

$$IE(Q(Z)) = \frac{U(Q (Z)}{\sum_{i=1}^{N} I(z_i)} \qquad (11)$$

where $Z = \{ z_1, z_2, . . . z_N\}$ is the set of information sources. IE can be used to evaluate how efficiently performance with an opportunistic protocol compared to the original protocol.

This last equation can be used to calculate information efficiency of a protocol. A useful application is to compare different opportunistic protocols for information efficiency. We can use IE in the next equation to evaluate how the system performance efficiency has been improved with an opportunistically designed protocol.

$$IE(Q(X^+, Z)) = \frac{U(Q(X^+, Z)) - U(Q'(Z))}{\sum_{i=1}^{N} I(x_i)} \qquad (12)$$

where Z is the set of information sources, Q′ is the original protocol and $X^+ = \{ x_1, x_2, \ldots x_n \}$ are the additional information sources used by the opportunistic protocol Q.

4. PERFORMANCE EVALUATION

In [1], the authors look at two opportunistic protocols. They look at the functionality of their framework and the impact of information quality on performance and they look at how to analyze and improve the information efficiency of the protocols using IE.

4.1 Information Quality

The network scenario used consistsof a base station (BS) serving four clients C_1, C_2, C_3, and C_4 in each time slot. Each client can have one of N discrete channel conditions. For simplicity, presume that each node is equally likely to have a “good” channel condition or a “bad” channel condition. Transmission rates on each channel are T_G = 1 Mb/slot and T_B = 0.5 Mb/slot, respectively.

Each client contains a transmission buffer of size k for outgoing messages. It’s message availability is measured by dividing the message length by the empty buffer size k. If the message availability is greater than or equal 50%, it’s transmission success probability is P_H, otherwise it’s transmission success probability is P_L. As the authors in [1], we set $P_H = 0.8$ and $P_L = 0.2$. Each client is equally likely to have high or low message availability. The performance metric under consideration is the average system throughput per slot.

4.2 Channel Condition Information

If the BS has no information about each clients channel condition, the BS serves the clients in random order. The entropy of channel condition information, the number of bits necessary to encode channel condition information for four clients is:

$$G_{rand} = (1 / 4) (T_G \times P_H + T_G \times P_L + T_B \times P_H + T_B \times P_L) \qquad (13)$$

$$= 0.375 \text{ Mb/slot}$$

Now presume the BS gets channel condition information from only one of its clients while the others remain unknown. This single bit may indicate either “good” or “bad” with equal probability. If the bit indicates “good”, the BS will schedule a transmission from this client. If the bit indicates “bad”, the BS will select one of the other clients for transmission. In this case, the expected average throughput becomes:

$$G = (1 / 2) \times ((1 / 2) \times P_H + (1 / 2) \times P_L) + (1 / 2) \times G_{rand} \qquad (14)$$

$$= 0.4375 \text{ Mb/slot}$$

Presume the BS gets channel condition information from two clients. These two bits can be one of four combinations with equal probability 1 / 4. The expected average throughput becomes G = 0.4688 Mb/slot. System throughput can also be calculated with three and four bits of channel condition information.

4.3 Message Availability Information

We also consider message availability information and its effect on performance. We follow the same logic used previously and derive results and the quantitative performance variations with message availability information. The results are shown in Table I.

Info	Entropy	G (channel)	G (message)
Nil	4 bits	0.375 MB/slot	0.375 Mb/slot
1 bit	3 bits	0.4375 Mb/slot	0.4875 Mb/slot
2 bits	2 bits	0.4688 MB/slot	0.5438 Mb/slot
3 bits	1 bit	0.4844 Mb/slot	0.5719 Mb/slot
4 bits	Nil	0.4844 Mb/slot	0.5719 Mb/slot

TABLE: IPerformance Variation Due to Information Availability

Looking at columns three and four, it is apparent that with more information available, performance is improved. A close examination shows that less information, as indicated by entropy, generates better performance. This is counterintuitive and is due to the fact that higher quality information is used to more efficiently improve performance.

We note that different information does have a different affect on performance, In particular, message availability information has a more significant impact on performance than channel condition information. Message availability information has higher information quality.

We compare our results for client to BS communication to the results obtained by Geng and Li [1] for BS to client communication. The results obtained by Geng and Li are shown in Table 2 [1].

Info	Entropy	G (channel)	G (message)
Nil	4 bits	0.375 MB/slot	0.375 Mb/slot
1 bit	3 bits	0.4375 Mb/slot	0.4875 Mb/slot
2 bits	2 bits	0.4688 MB/slot	0.5438 Mb/slot
3 bits	1 bit	0.4844 Mb/slot	0.5719 Mb/slot
4 bits	Nil	0.4844 Mb/slot	0.5719 Mb/slot

TABLE 2 Results of Geng and Li

A close comparison shows that our results for client to BS communication exactly mathes the results of Geng and Li for BS to client communication. This serves to show that communication in both directions show equal performance improvements by applying the concepts of information quality and information efficiency

4.4 Information Efficiency

In this scenario we consider time slotted opportunistic scheduling. The network scenario of a BS serving three clients. Each client has two possible channel conditions, s_1 and s_2, and performance values, throughput G_1 and G_2 with $G_1 > G_2$. In any slot, each client is equally likely to be in states s_1 or s_2. As the authors in [1], we look at the temporal fairness requirement in [9] and set $r_1 = r_2 = r_3 = 1 / 3$, each user should be allocated one-third of the transmission time.
Using non-opportunistic scheduling, with no channel condition information, the average performance is:

$$E[\, U_{Q'(u)}] = \sum_{i=1}^{3} r_i \times E[\, U_i \,] \qquad (15)$$

$$= (\, G_1 + G_2 \,) / 2$$

where $Q'(\,U\,)$ is a non-opportunistic schedule and $E[\,U_i\,]$ is the expected performance of client i, and $E[\,U_{Q'(\,U\,)}\,]$ is the average performance. With no channel condition information, the BS chooses clients randomly.

Now, with opportunistic scheduling used with channel condition information available from each client, the BS can choose the most favorable client and the average system performance becomes:

$$E[\, U_{Q(\,s1,\, s2\, u)}] = \sum_{i=1}^{3} r_i \times E[\, U_i \,] \qquad (16)$$

$$= (7 G_1 + G_2) / 8$$

The IE of the opportunistic scheduling protocol Q(s_1, s_2, U) is:

$$IE(Q(s_1, s_2, U)) = \frac{E[U_{Q(s1, s2, U)}] – E[U_{Q'(U)}]}{3 \text{ bits per slot}} \quad (17)$$

$$= (G_1 – G_2) / 8$$

We also ask if all possible information is necessary. We presume that only clients with "good" channel condition information report their channel condition s_1. Indeed, using only s_1 as the information available, the IE improves to:

$$IE(Q(s_1, U) = \frac{E[U_{Q(s1, s2, U)}] – E[U_{Q'(U)}]}{1.5 \text{ bits/slot}} \quad (18)$$

$$= (G_1 – G_2) / 4$$

5. CONCLUSION

Geng and Li [1] presented an information theoretic framework to analyze network performance. In that work, the authors considered only the transmission from the BS to the clients. In this paper, we used the framework to analyze network performance when transmitting from the clients to the BS. Using the same scenarios as used in [1], we generate the same results. The quality of information available does affect system performance for the better. Our results provide further validation to the theory of an information theoretic framework for analyzing protocols and network performance.

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