Throughput Enhancement with HARQ in Wireless Relay Networks

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Abstract. We propose an optimal method that maximizes the end-to-end throughput in wireless multi-hop relay networks where hybrid automatic repeat request (HARQ) protocols are employed. The proposed method estimates the end-to-end expected throughput based on the operation principle of HARQ, while considering multi-hop relaying and block fading channel. We prove the throughput from our method is higher than or equal to that from the conventional method for any error probability.

Keywords: HARQ, Multi-hop replaying, Expected throughput

1 Introduction

Recently, multi-hop relay schemes have been considered to enhance coverage, capacity, and quality-of-service (QoS) performance of the conventional single-hop networks [1]. The schemes take advantages of the reduction in the overall path loss between source and destination nodes by intermediate relay nodes. Through these nodes, the cell coverage can be effectively extended to heavily shadowed areas. Therefore, to provide throughput enhancement at the cell edge, fourth-generation (4G) cellular systems such as 3GPP LTE and IEEE Task Group m (IEEE 802.16m) have also adopted the schemes [2,3].

With these trends, we investigate how to maximize the end-to-end throughput of multi-hop relay networks where HARQ protocols are employed in this paper. We propose a novel method that estimates the end-to-end expected throughput based on the operation principle of HARQ, while taking into account not only multi-hop relaying but also block fading channel.

2 System Model

The network model under consideration is illustrated in Fig. 1. We consider a linear wireless K-hop relay model that consists of a source node s (Fo), a destination node d *(FK),* and $K-1$ intermediate relay nodes which are equidistantly

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placed on a line from **s** to **d.** The linear network topology facilitates the analysis of the multi-hop relay schemes and arranging all relay nodes on a line at equidistance is an optimal deployment policy in terms of throughput and energy consumption [4]. All the nodes are assumed to employ half-duplex transmissions with a fixed power P per coded symbol and they fully decode the original packet received from the preceding node, to re-encode it, and to forward it to the following node. No spatial reuse is allowed so that the successful delivery of a packet from **s** to **d** requires at least K transmissions. We assume that a packet should be delivered within a given maximum transmission delay N_{max} and, for simplicity, the unit of this delay is assumed to be equal to either one transmission interval or one HARQ round. If **d** does not receive a packet after K transmissions, Nmax — K transmissions remain for retransmissions and, on each hop that fails the successful packet forwarding, the retransmissions are performed with HARQ operations.
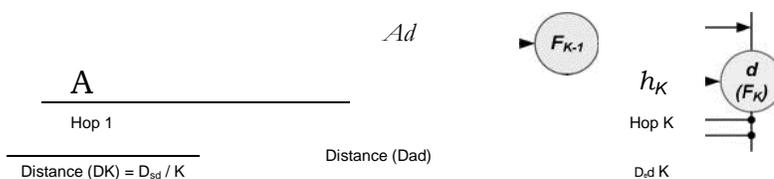

Fig. 1. Linear wireless K-hop relay model.

We consider a block fading channel model in which the channel state is time-invariant over one transmission interval and it independently changes with each interval. In Fig. 1, channel gains $h_s^{(n)}{}_d$ and $h^{(n)}$ are independent zero mean circular symmetric complex Gaussian variables with the respective variances of $o_s d$ and Ok. Assuming the distance-dependent path loss model, $o_s^- d$ and ak are expressed as

$$Usd = \left(\frac{D_0}{} \right) \text{ and } ak = \left(\frac{D_0}{Do}\right)— \tag{1}$$

where D_o is the reference distance and n is the path loss exponent. In our network model, DK is set to D_{sd}/K and all a_k have the same values. The signal from sender to receiver is perturbed by the complex additive white Gaussian noise (AWGN) with zero mean and variance N_o. In this paper, a block length, i.e., the number of channel uses is assumed to be sufficiently large for a single HARQ round. Thus the decoding failure at each HARQ round is well matched to the information outage probability through the use of good code sequences [5].

3 Maximizing the End-to-end Expected Throughput

We present two methods that estimate the end-to-end expected throughput in a linear K-hop relay network in which HARQ operation is performed. The first

method proposed in [6] estimates the expected throughput based on the renewal theory (RTT). For a given maximum transmission delay $N_{oia,,}$ the RTT is expressed as

$$RTT \quad \lim_{t \to c \bullet 0} \frac{r(t)}{t} \quad E[T] Nr_{,,,,} - 1 \quad \frac{R(1 - Pout(Nmax))}{K \quad \mathop{E}_{n=K} Pout(n)}$$
(2)

where $r(t)$ is the reward process which earns a reward r_n at the time of the n-th renewal event and the third term in (2) is obtained using the asymptotic properties of renewal theory. $R(b/s/Hz)$ is a transmission rate and $P_{out}(n)$ is the outage probability after n transmissions. Consequently the fourth term in (2) is the long-term average throughput in which the numerator indicates the average spectral efficiency obtained after N. transmissions and the denominator indicates the average number of transmissions over K hops. $P_{out}(n)$ is obtained by counting all events that destination node successfully receives a packet sent from source node through K hops until n transmissions. It is expressed as

$$P_{out}(n) = 1 - \mathop{}_{m=K \ L_{,,}, \ k=1} ft \ P8(/k).$$
(3)

$P_8(1k)$ is the successful decoding probability of a packet
after $/k$ transmissions in the k-th hop and $E_{L\_}(.)$ is the summation of (.) over all the tuples in the set

$L_m = \{(11, \bullet\bullet\bullet \quad E \ N, /1 + \bullet\bullet\bullet + /K = m\}$. Thus $E_{Lra}n_iK\_, Ps(4)$ denotes the probability that a packet is successfully delivered from source to destination nodes through K hops after m transmissions. Furthermore the event that the k-th receiver successfully decodes a packet after $/k$ transmissions occurs when it fails to decode the packet until $/k - 1$ transmissions. Thus $P_s(1k)$ is expressed as $Pf(lk - 1) - Pf(lk)$ and which is equal to $ft\_k \ i^t \ P_e(l)(1 - 1^3,(1k))$ where $Pf(lk)$ and $P_e(1)$ are the decoding failure probabilities of a packet after $/k$ transmissions and at the l-th transmission, respectively.

In [6], the RTT is proposed as the expected throughput which is used in a block fading channel. However, we address that, in this channel, the RTT cannot be the exact expected throughput. In (2), the asymptotic properties hold when the inter-renewal time is independently and identically distributed (i.i.d.) and, to obtain the RTT, this time presents a packet transmission time which is determined by a channel state. Since the inter-renewal time is i.i.d., the channel state is time-invariant and the outage probability is fixed as time tends to infinity. However, in the block fading channel, the channel state in the n-th packet delivery is not i.i.d. with that in the n+l-th packet delivery. Consequently the RTT which is obtained based on the underlying assumption of time-invariant channel state cannot be the expected throughput in this channel.

Motivated by the above fact, we propose a novel method that exactly estimates the end-to-end expected throughput for a block fading channel in linear K-hop relay network. In [7], we proposed the expected throughput estimation method for single-hop networks. The method exploits the operation principle of HARQ and, in this paper, we extend this method to reflect a linear K-hop relay

network, without loss of generality. In a single-hop network with HARQ, if a packet with the transmission rate of R is repeatedly sent n times, the rate is reduced to R/n at the n-th transmission. And the throughput obtained at the n-th transmission is calculated by multiplying R/n with the successful decoding probability of a packet after n transmissions. Thus the expected throughput obtained after N_{max} transmissions becomes to be the summation of the throughput calculated at each transmission. In a K-hop relay network with HARQ, based on the above concept, the end-to-end expected throughput after N_{max} transmissions is the summation of the throughput which is calculated by multiplying R/n with the probability that a packet is successfully delivered through K hops after n transmissions. We name the throughput obtained from our proposed method as constrained-delay-based throughput (CDT) and it is expressed as

$$CDT = R \sum_{n=K}^{Nmax} L_n \sum_{k=1}^{} {}_H P_s(1k) = R \sum_{n=K}^{Nma.} {}^{-1} (P_{out}(n-1) - P_{out}(n)) \quad (4)$$

The CDT considers the time-varying channel states which are changed at each transmission. Thus it is the end-to-end expected throughput while taking into account the individual throughput obtained at every packet delivery, instead of approximating the long-term average throughput, as in the RTT.

4 Numerical Analysis

We investigate the performance of our CDT-based method and that of multi-hop relaying scheme employing HARQ protocols, through the numerical simulations. Two maximization problems have been discussed in [6] and, in this paper, we also issue these problems with both the RTT- and CDT-based methods. This is because an optimal design for multi-hop relay networks is achieved by solving two problems and it is necessary to analyze the performance of our CDT-based method with these problems. The first problem finds the transmission rate R. with the CDT, which is mandatory to fully utilize the HARQ performance for a given SNR. And, Using R_{max} obtained, the second problem finds the optimal number of hops $\&_{IA}$ with the CDT. We exhaustively searches R. and K_0 and if the maximum transmission delay N_{max} is not large, this search would be acceptable in terms of memory and processing demands.

Figure 2 shows the throughput versus transmission rate for given $n = 3$, $p = -10$ dB, Nmax = 14, and $1 < K < 10$ while the CC-based HARQ mechanisms is considered. The result shows that the CDT is higher than or equal to the RTT for all transmission rates. For a given K, both the CDT and RTT increase until the transmission rate R increases to the optimal value R_{max}. This is because, in $0 < R < Rmax$, the increased rate is a dominant factor to determine the throughput. On the other hands, in $R > Rmax$, the throughput becomes to be dominantly determined by the outage probability. Moreover, All R. obtained form both the CDT- and RTT-based methods constantly increase until the number of hops K increases to the optimal value K_{opt}. This is because, in $0 < K < K_{opt}$, the

improvement in the path-loss reduction leads to the increase in the transmission rate. On the other hands, in $K > K_{opt}$, the increased delay due to multi-hop relaying becomes to be a dominant factor to determine the throughput.
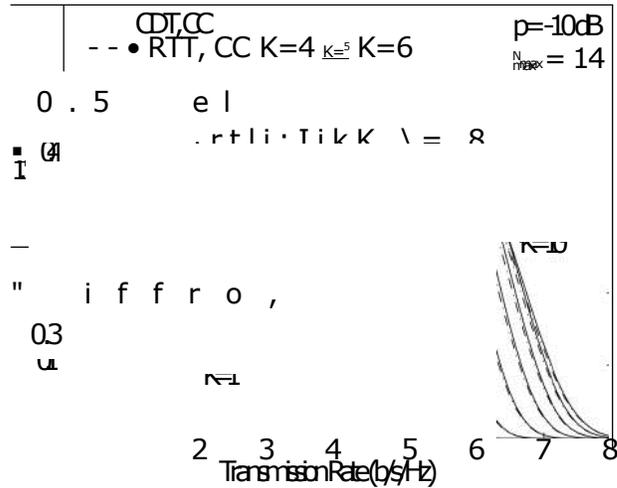

Fig. 2. Throughput vs. transmission rate for given $n = 3$, $p = -10$dB, $N_{max} = 14$, and $1 < K < 10$: CC-based HARQ mechanism.

Figure 3 shows the throughput versus transmission rate for given $n = 3$, $p = -10$ dB, Nmax = 14, and $K = 1, 4, 7, 10, 13$ while both the CDT and RTT are obtained with the upper bound of IR, and each of which is compared with the IR-based average throughput obtained through Monte-Carlo simulations. In Fig. 3(a), the CDT with the upper bound of IR outperforms the average throughput with IR for given all K. And an important result is shown in Fig. 3(b) that, even though the RTT is obtained with the upper bound of IR, it yields lower throughput than the IR-based average throughput. Through the result, we precisely conclude that the RTT-based method cannot yield the exact end-to-end expected throughput in the block Rayleigh fading channel and, moreover, wrong Rmax and K_0 would be selected with the RTT-based method.

5 Conclusion

In this paper, we have studied how to maximize the end-to-end throughput of wireless multi-hop relay networks which employ HARQ protocols. We have considered a linear K-hop relay model and have proposed a novel method that exactly estimates the end-to-end expected throughput in a block fading channel. From the numerical results, we have concluded that the proposed method has better performance than the previous RTT-based method in the block Rayleigh fading channel.
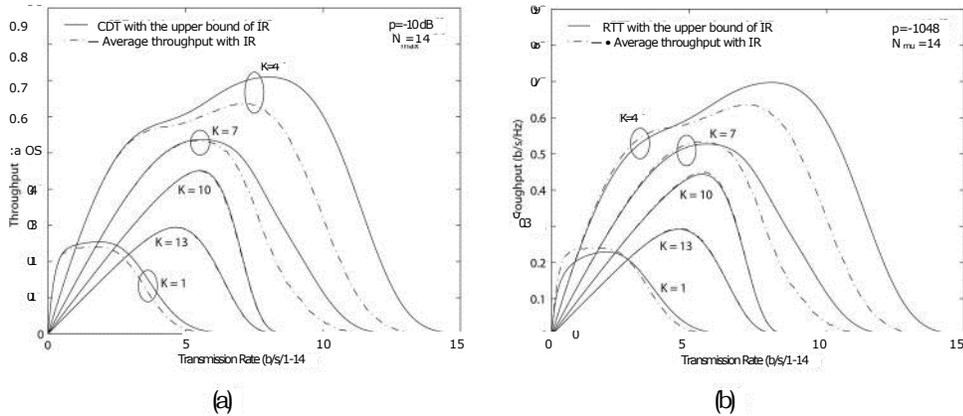
Fig. 3. Throughput vs. transmission rate for given = 3, $p = -10$dB, Nmax = 14, and $K = 1,4,7,10,13$: (a) Comparison between the CDT with the upper bound of IR and average throughput with IR. (b) Comparison between the RTT with the upper bound of IR and average throughput with IR.

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