Performance Evaluation of Split Transmission in Multihop Wireless Networks

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Abstract. Multimedia applications in multihop wireless networks have great market potential. Multiple channels and multiple radios are commonly used for exploring multimedia transmissions in multihop wireless networks. Split transmission allows multiple channels attached to different radios simultaneously to be used, and so to achieve a fundamentally improved transmission capacity. The goal of this paper is to present a theoretical background to justify the improved performance of split transmission. We theoretically study and prove that, by using the split transmission, the worst-case delay is decreased to $\frac{\sigma\rho_{k-1}}{LC_{m-1}C_{k-1}}$ of that without using split transmission, the average throughput is increased to $\frac{1}{1-\prod_{j=0}^{k-1}\alpha_j}$ of that without using split transmission, and the average delay jitter is decreased to $\frac{C_{k-1}C_\rho}{C_{m-1}[C_\rho+L(\rho+C)]}$ of that without using split transmission. We believe that this is the first attempt to consider split transmission in theory.

Key Words: Wireless Multimedia, Split Transmission, Performance Evaluation, Multiple Channels, Multiple Radios.

1 INTRODUCTION

A multihop wireless network (e.g. an ad hoc network, sensor network, mesh network) is a self-organized and self-configured wireless architecture in which two wireless nodes communicate through a number of intermediate nodes, whose functions are to relay data one by one. Multihop wireless networks have multiple advantages: reliable coverage, robustness, and easy maintenance to facilitate interactive multimedia communications that are in great market demand. Examples of multihop wireless multimedia applications are online games, wireless video conferences, online exchange, real-time monitoring of activities at homes and in offices, etc. However, communications over wireless links are subject to channel fading, multipath fading, and interference from background noise and neighbours, which degrade the performance of multimedia communications.

To improve the degraded multimedia performance, a considerable amount of research has studied multimedia transmission algorithms/schemes in multihop wireless networks. One approach [1-3] focuses on switching multiple channels on the same radio interfaces. An alternative line of research [4-9] exploits the advantage of multiple radio interfaces for multimedia transmissions. However, few of them work for an interactive multimedia transmission which particularly requires a high quality transmission in a real-time way. We designed a *split multimedia transmission* in [10]. The algorithm uses multiple radio interfaces in parallel to transmit a multimedia stream that will suffer from a bottleneck. Our simulation results in [10] observed that the algorithm fundamentally improves multimedia performance. In this paper, we present a theoretical background to explain the performance improvement of split transmission. We believe this is the first attempt to study split transmission in theory.

The acceptable performance of interactive multimedia communications requires uninterrupted and distortionless content reception within stringent delay constraints. These requirements can be expressed as three metrics of worst-case delay, average throughput, and average delay jitter. An end-to-end delay is the time taken for a packet to transmit across a network from a source to a destination. It is the summation of the packet's transmission delay, propagation delay and processing delay. A worst-case delay, evaluated in real time, is the longest end-to-end delay of a multimedia transmission. Throughput is the average rate of successful message delivery over a channel. Average throughput affects the definition of multimedia playback. Delay jitter is defined as the difference in end-to-end delays between selected packets in a flow with any lost packets being ignored [16]. Another well-known definition of delay jitter is in [15] which considers the standard deviation of packet delays. This paper uses the definition in [16] because we feel it is more directly related to the user experience. Average delay jitter evaluates the continuity of a multimedia transmission. Large delay jitter causes interrupted multimedia playback. This paper mathematically evaluates these three metrics in a multihop split multimedia transmission.

There are two classical ways to model multimedia traffic: a leaky bucket [11-12] and a (σ, ρ) regulator [13-14]. The leaky bucket enforces a rigid output pattern at the average rate ρ no matter how bursty the input traffic is. For multimedia traffic, a more flexible mechanism is required to process large burstiness that allows the short delay output, preferably one that does not lose data. The (σ, ρ) regulator introduces burstiness into the traffic model. Thus, we employ the (σ, ρ) regulator to model multimedia traffic in our theoretical evaluation, and present the following results for a multimeida stream f transmitted in a k-hop wireless network. (Suppose there are m radios selected by the split transmission.)

- The worst-case delay of split transmission is bounded above by $\frac{k\sigma}{C_{m-1}} + \frac{kL}{C_{m-1}}$, where L is the average packet size of the multimedia stream and C_{m-1} is the transmission capacity of the last (i.e. $(m-1)$th) selected channel; the worst-case delay of non-split transmission is $kL\frac{1+C_{k-1}^2}{C_{k-1}\rho_{k-1}}$, where ρ_{k-1} and C_{k-1} are the average transmission rate and the output capacity at the last (i.e. $(k-1)$th) hop;
- The average throughput of split transmission is $\rho + \frac{\sigma}{\Delta t}$, where Δt is the time that has elapsed since the initial transmission of f; the average throughput of non-split transmission is bounded above by $(1 - \prod_{j=0}^{k-1} \alpha_j)(\frac{\sigma}{\Delta t} + \rho)$, where α_j is the packet loss rate at the jth hop ($j \in [0, k-1]$);
- The average delay jitter of split transmission is $k\frac{\rho - C_{m-1}}{C_{m-1}}[t_l - t_{l-1}]$, where t_l and t_{l-1} are the transmission times of the lth and the $(l-1)$th packets; the average delay jitter of non-split transmission is $\frac{k}{\rho}(\frac{\rho}{C_{k-1}} - 1)[(\frac{\rho}{C_{k-1}} - 1)\Delta t_{k-1,p-1} + (t_l - t_{l-1})]$, where $\Delta t_{k-1,p-1}$is the time that has elapsed to transmit the $(p-1)$th packet at the $(k-1)$th hop since f's initial transmission.

We then observe the split transmission with simulations in ns-2 [19]. Both the theoretical analyses and simulation evaluation prove that the split transmission is an effective way to achieve short delay, high throughput, and continuous wirele ss multimedia performance. While modern technology is still developing to open wider implementation for split transmission, the algorithm promises to be used currently to solve burstiness without changing the existed wireless hardware and MAC protocols.

This paper is organized as follows. Section 2 introduces the related work. Section 3 briefly details the split transmission algorithm. In section 4, we analyze the performance of worst-case delay, average throughput, and average delay jitter. Section 5 uses ns-2 simulations to evaluate split transmission. Section 6 concludes this paper.

2 Related Work

Related studies for wireless multimedia transmission mainly focus on algorithm /protocol design to achieve some anticipated performance. These works can be classified as *multi-channel single interface schemes* and *multi-channel multi-interface schemes*.

Protocols in [1-3] are *multi-channel single interface schemes* that make use of the capacities of multiple channels on the same radio interface. [1] proposed SSCH (slotted seeded channel hopping) that slots the time for nodes to hop between multiple channels without incurring transmission interference. A global time is required to synchronize channel selection between nodes. Also, hopping between channels creates transmission jitter. J. So *et al* [2] designed a medium access control protocol that dynamically uses temporal synchronization to solve the hidden terminal problem in ad hoc networks. The protocol also requires a complex global clock. S. Wu *et al* [3] proposed a RTS/CTS like reservation mechanism to dynamically assign channels to mobile nodes in an "on-demand" way. Generally, *multi-channel single interface protocols* cannot avoid collision because multiple channels attach to the same interface. Complex algorithms are required to decrease collisions and as well to maintain a global clock.

Another approach is to utilize the advantage of multiple interfaces to assign a different radio interface to each individual channel. P. Kyasanur *et al* [8] presented a channel assignment protocol in the context of multi-radio wireless mesh networks. Each node has some fixed channel and is also dynamically connected to other channels over short time. A sender then adapts to a receiver by changing its temporary channel to the receiver's fixed channel. A. Adya *et al* [4] presented a multi-radio unification protocol for multihop wireless mesh networks with the goal to optimize local spectrum utilization through intelligent channel selection. A. Raniwala *et al* [6] proposed a centralized greedy solution that accesses wireless links in decreasing order of link loads. The solution cannot deal with dynamic traffic load. Hence, A. Raniwala *et al* [7] extended this study to a distributed algorithm. The designed architecture (called Hyacinth) uses local traffic load information to dynamically assign channels and route packets. In general, through selecting an individual optimal channel for each traffic, the improved performance achieved by most *multi-channel multi-interface schemes* is limited by each individual channel's capacity.

Our split transmission [10] aggregates capacities from multiple radios for the use of one multimedia stream. The performance is considerably improved as compared to other algorithms. We are interested in explaining such improvement theoretically in this paper.

3 Split Transmission

The motivation of split transmission is to simultaneously use multiple interference-free channels to transmit QoS guaranteed multimedia streams. As illustrated in Fig. 1, when a wireless node detects a coming overload in an output channel because of transmitting a multimedia stream f, it selects m channels (labeled as dotted lines in the coverage of node 2 in the figure) that attach to m different radios to transmit the stream together. In split transmission, the number of selected channels is the minimum to guarantee a total capacity that is enough for carrying f. That is, if m channels are selected, the following expression exists.

$$\begin{cases} C(\hat{0},t) + C(\hat{1},t) + ... + C(\hat{i},t) + ... + C((m \hat{-} 1),t) \geq r_f, \\ C(\hat{0},t) + C(\hat{1},t) + ... + C(\hat{i},t) + ... + C((m \hat{-} 2),t) \leq r_f, \end{cases}$$

where t is the time at which the node uses the split transmission, r_f is f's transmission rate, and $C(\hat{i},t)$ is the ith selected channel's capacity at the time t. Based on each selected channel's individual capacity, the wireless node splits the multimedia stream into m subflows. Each subflow has a transmission rate r_i ($i \in [0, m-1]$) matching the capacity of one selected channel $C(\hat{i},t)$. Namely, $r_i = C(\hat{i},t)$. Then these m subflows will be transmitted through the m selected channels in parallel as shown in Fig. 1.

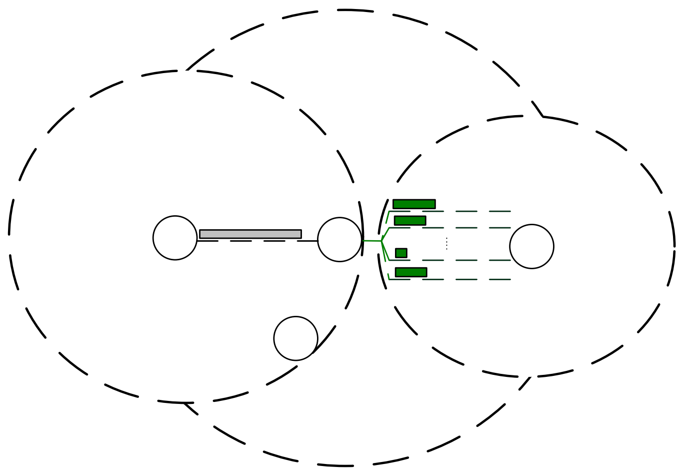

Fig. 1. An example of split transmission.

Split transmission has been proved to be effective in decreasing transmission delays, improving transmission throughput, and reducing delay jitter for wireless multimedia transmission by our simulations [10]. In this paper, we mathematically study the split transmission to present a theoretical background for the improved performance.

4 Performance Evaluation for Split Transmission

To implement the analysis, as introduced, we use a (σ, ρ) regulator to model multimedia traffic. In [13], the (σ, ρ) regulator is defined as
Given $\sigma > 0$ and $\rho > 0$, for an input flow with the rate function R, the following inequality exists if and only if $y \geq x$ for all x and y,

$$\int_x^y R dt \leq \sigma + \rho(y - x), \tag{1}$$

where ρ is the flow's average input rate and σ is the flow's burst constraint. According to (1), the upper bound of the amount of multimedia traffic input into the network between the times y and x is decided by the traffic burstiness σ and the traffic average transmission rate ρ.

Before we analyze the performance of worst-case delay, average throughput, and average delay jitter, we list the symbols that will be used for analysis in Table 1.

Table 1. Symbol List

f	Represent a multimedia stream.
m	The number of selected channels/interfaces in the split transmission.
$\dot{C}_i$	The capacity of the ith selected channel, $i \in [0, m-1]$.
k	The number of hops from a sender to a receiver in the multihop wireless network.
C_j	The output capacity at the jth hop in the non-split transmission, $j \in [0, k-1]$.
L	The average packet size of f.
Δt	The elapsed transmission time since f is initially transmitted.
p	The total number of packets in f.
Δt_l	The elapsed transmission time when transmitting the lth packet, $l \in [0, p-1]$.
$\Delta t_{j,l}$	The elapsed transmission time when transmitting the lth packet of the jth hop.

4.1 The Worst-Case Delay

The worst-case delay, evaluated in real time, is the longest end-to-end delay between a sender and a receiver. We first consider the worst-case delay in a single hop wireless network. According to the definition of the (σ, ρ) regulator, the transmission rate of f is $R \sim (\sigma, \rho)$. When f is split into m subflows that are denoted as $f_i (i \in [0, m-1])$, each subflow's transmission rate satisfies $R_i \sim (\sigma_i, \rho_i)$, where R_i, σ_i, and ρ_i are f_i's input rate, burstiness, and average transmission rate respectively. Use C_i to represent the ith selected channel's available capacity. The transmission delay of the ith subflow at the time t is

$$D_i = \frac{[\sigma_i + \rho_i \Delta t] - [C_i \Delta t - L]}{C_i}, \tag{2}$$

where $\Delta t = t - t_0$ (t_0 is the time that f is initially transmitted by the node) and L is the average packet size of f. The item $[\sigma_i + \rho_i \Delta t]$ is the upper bound of f's input data amount in the period Δt. The item $[C_i \Delta t - L]$ is the amount of f's output data in the period Δt.

Based on (2) and $C_i \geq \rho_i$, it can be inferred that the worst-case delay of f_i is $\ddot{D}_i \leq \frac{\sigma_i + L}{C_i}$. Moreover, the worst-case delay $\ddot{D}_i$ appears at the time $(t_0 + \frac{L}{C_i})$ and decreases to 0 after a period of $\frac{\sigma_i + L}{C_i - \rho_i}$.

Considering all of the m split subflows, the worst-case delay in a single hop wireless network is $\ddot{D}_s = max\{\ddot{D}_i | i \in [0, m-1]\} = max\{\frac{\sigma_i + L}{C_i} | i \in [0, m-1]\}$. Without loss of generality, we assume $C_0 \geq C_1 \geq C_2 \geq ... \geq C_{m-1}$ for the m subflows. This assumption indicates $\frac{\sigma}{C_{m-1}} \geq max\{\frac{\sigma_i}{C_i}\}$. Hence, we have

$$\ddot{D}_s \leq \frac{\sigma}{C_{m-1}} + max\{\frac{L}{C_i}\} \leq \frac{\sigma}{C_{m-1}} + \frac{L}{C_{m-1}}. \tag{3}$$

We now extend our analysis into a k-hop ($k > 1$) wireless network. In split transmission, packet queueing time can be neglected since subflows are generated based on the capacities of selected output channels. For interactive multimedia communications in which traffic comes continuously, the selected multiple channels are reserved for transmission and therefore the time used by channel selection and channel capacity collection in split transmission is avoided. Hence, an end-to-end delay is the summation of packet delays at all hops from a sender to a receiver. That is, the worst-case delay when f experiences k-hop split transmission is

$$\ddot{D} \leq k\ddot{D}_s \leq \frac{k\sigma}{C_{m-1}} + \frac{kL}{C_{m-1}}. \tag{4}$$

We next analyze the worst-case delay of multimedia traffic without employing split transmission. The end-to-end delay in a single hop wireless network is

$$D'_s = \frac{(\sigma + \rho\Delta t) - C(\Delta t - \frac{L}{\rho} - \frac{L}{\rho - C})}{C},$$

where C is the available capacity of f's output channel. In a k-hop wireless network, based on the expression above, the packet transmission delay at the

jth hop is

$$D'_j = \frac{(\sigma_j + \rho_j \mathit{\Delta} t) - C_j(\mathit{\Delta} t - \frac{L}{\rho_j} - \frac{L}{\rho_j - C_j})}{C_j}, \tag{5}$$

where $j \in [0, k-1]$, σ_j and ρ_j are f's burstiness and average transmission rate at the jth hop, and C_j is output capacity at the jth hop. It shows that the total end-to-end delay when f transmits k hops is calculated by

$$D' = \sum_{j=0}^{k-1} D'_j = \sum_{j=0}^{k-1} \frac{(\sigma_j + \rho_j \mathit{\Delta} t) - C_j(\mathit{\Delta} t - \frac{L}{\rho_j} - \frac{L}{\rho_j - C_j})}{C_j}. \tag{6}$$

To develop (6), we know that the k-hop non-split transmission has these characteristics: $\sigma_j \geq \sigma_{j+1}$, $\rho_j \geq \rho_{j+1}$, $C_j \geq C_{j+1}$, and $C_j \mathit{\Delta} t = \sigma_{j+1} + \rho_{j+1} \mathit{\Delta} t$. Hence, it can be inferred that

$$\begin{aligned} D' &\leq \frac{\sigma_0 + \rho_0 \mathit{\Delta} t}{C_0} + ... + \frac{\sigma_{k-1} + \rho_{k-1} \mathit{\Delta} t}{C_{k-1}} - [k \mathit{\Delta} t - k \frac{L}{C_{k-1} \rho_{k-1}} - k \frac{L}{C_k(\rho_k - C_k)}] \\ &\leq k \mathit{\Delta} t - [k \mathit{\Delta} t - k \frac{L}{C_{k-1} \rho_{k-1}} - k \frac{L}{C_{k-1}(\rho_{k-1} - C_{k-1})}] \leq kL \frac{1 + {C_{k-1}}^2}{C_{k-1} \rho_{k-1}}. \end{aligned} \tag{7}$$

The worst-case delay of non-split multimedia transmission in a k-hop wireless network is therefore

$$\ddot{D}' = kL \frac{1 + {C_{k-1}}^2}{C_{k-1} \rho_{k-1}}.$$

To calculate the worst-case delay improvement of split transmission, we have

$$\frac{\ddot{D}}{\ddot{D}'} = \frac{(\sigma + L) C_{k-1} \rho_{k-1}}{C_{m-1} L (1 + {C_{k-1}}^2)} \approx \frac{\sigma \rho_{k-1}}{L C_{m-1} C_{k-1}}. \tag{8}$$

Since $L >> m$, we have $\sigma < LC_{m-1}$. Usually, $\rho_{k-1} \leq C_{k-1}$. Hence, $\frac{\ddot{D}}{\ddot{D}'} < 1$. Furthermore, $\ddot{D}$ comes into existence at the time $t_0 + \frac{L}{C_{m-1}}$. When the transmission continues, the end-to-end delay of split transmission reduces to 0 while the end-to-end delay of non-split transmission increases further to the maximum value of $kL \frac{1 + (C_{k-1})^2}{C_{k-1} \rho_{k-1}}$.

4.2 The Average Throughput

The average throughput evaluates the playback quality (i.e. video definition and audio articulation) of multimedia traffic. We first consider the average throughput of split transmission in a single hop wireless network. Each of the m selected channels has enough capacity to output one split subflow. It shows that the total output packets of f through the m channels should be equal to f's input amount. Thus, in a single hop wireless network,

$$\sum_{i=0}^{m-1} [C_i(\mathit{\Delta} t - \frac{L}{\rho_i})] = \sigma + \rho \mathit{\Delta} t.$$

Based on the above equation and $\rho_i \leq \rho$, we have

$$\sum_{i=0}^{m-1} C_i = \frac{(\sigma + \rho\Delta t)\rho}{\rho\Delta t - L} \approx \rho + \frac{\sigma}{\Delta t}. \tag{9}$$

For the average throughput in a k-hop wireless network, multimedia transmission at each hop is able to output all received packets. It means that each hop achieves the average throughput in (9). Hence, the average through of the split transmission after k hops is $\bar{T} = \rho + \frac{\sigma}{\Delta t}$.

We now consider the average throughput of non-split transmission in a k-hop wireless network. Assume the loss rate at the jth hop transmission is α_j ($j \in [0, k-1]$). The following equation is established based on the fact that the difference between the input amount and the output amount is equal to the amount of lost packets.

$$\sigma + \rho\Delta t - C_{k-1}(\Delta t - \frac{L}{\rho} - \frac{L}{\rho - C_{k-1}}) = \prod_{j=0}^{k-1} \alpha_j(\sigma + \rho\Delta t).$$

This equation infers that the average throughput with the split transmission is

$$T' \leq \frac{\rho(\sigma + \rho\Delta t)(1 - \prod_{j=0}^{k-1} \alpha_j)}{\rho\Delta t - 2L} \approx (1 - \prod_{j=0}^{k-1} \alpha_j)(\frac{\sigma}{\Delta t} + \rho). \tag{10}$$

To compare the average throughput of split transmission and non-split transmission in a k-hop wireless network, we use the following equations.

$$\frac{T}{T'} = \frac{1}{1 - \prod_{j=0}^{k-1} \alpha_j}.$$

As compared to non-split transmission, the improvement in the average throughput of split transmission increases when f traverses larger numbers of hops. It proves that the split transmission suits multihop wireless multimedia transmissions.

4.3 The Average Delay Jitter

The average delay jitter is the metric that evaluates the continuity of multimedia traffic. Small average delay jitter benefits smoothing video playback and uninterrupted audio reception. According to (2), the end-to-end delay of split multimedia transmission decreases to 0 after a period of $\tau = \max\{\frac{\sigma_i + L}{C_i - \rho_i} | i \in [0, m-1]\}$. The average delay jitter is therefore 0 after the period τ. Hence, we focus on analyzing the average delay before the time $(t_0 + \tau)$.

Suppose there are p_i ($p_i \in N$) packets transmitted in total from the sender to the receiver through the ith selected channel. We use $D_{i,l}$ and $D_{i,(l-1)}$ ($l \in [0, p_i - 1]$) to represent the end-to-end delays of the lth and the $(l-1)$th packets transmitted through the ith channel. Then, the delay jitter between the jth and the $(j-1)$th packets is $J_{i,l} = D_{i,l} - D_{i,(l-1)}$. According to (2),

$$J_{i,l} = D_{i,l} - D_{i,(l-1)} = (\frac{\rho_i}{C_i} - 1)(\Delta t_l - \Delta t_{l-1}). \tag{11}$$

In the split multimedia transmission, for the same reason as in Section 4.1, packet queueing time can be neglected. Hence, $\Delta t_l - \Delta t_{l-1} = t_l - t_{l-1}$. This implies that $J_{i,l} = (\frac{\rho_i}{C_i} - 1)(t_l - t_{l-1})$. Thus, the average delay jitter of split multimedia transmission in a single hop wireless network is

$$\bar{J}_s = \frac{\sum_{i=0}^{m-1}\sum_{l=0}^{p_i-1} J_{i,l}}{\sum_{i=0}^{m-1} p_i} = \frac{\sum_{i=0}^{m-1}\sum_{l=0}^{p_i-1}(\frac{\rho_i - C_i}{C_i})(t_l - t_{l-1})}{\sum_{i=0}^{m-1} p_i}$$

$$\le \frac{\sum_{i=0}^{m-1}\sum_{l=0}^{p_i-1}(\frac{\rho - C_{m-1}}{C_{m-1}})(t_l - t_{l-1})}{\sum_{i=0}^{m-1} p_i}^{1} = \frac{\rho - C_{m-1}}{C_{m-1}}(t_l - t_{l-1}). \tag{12}$$

Based on (12), the average delay jitter when f is in a k-hop wireless split transmission is

$$\bar{J} = \sum_{i=0}^{k-1} J_i = kJ_i = k\frac{\rho - C_{m-1}}{C_{m-1}}[t_l - t_{l-1}]. \tag{13}$$

We now consider the average delay jitter of non-split multimedia transmission. Suppose p is the total amount of packets that f has. Obviously, $p = \sum_{i=0}^{m-1} p_i$. According to our analysis in (5), the delay jitter $J'_{j,l}$ of the lth packet at the jth hop is

$$J'_{j,l} = \frac{\rho_j - C_j}{C_j}(\Delta t_l - \Delta t_{l-1}).$$

For the non-split transmission, $\Delta t_{j,l} - \Delta t_{j,(l-1)} = \frac{(\rho_j - C_j)\Delta t_{j,l}}{C_j} + t_l - t_{l-1}$, where $\frac{(\rho_j - C_j)\Delta t_{j,l}}{C_j}$ is the queueing delay of the packets that are transmitted at the time $t_{j,l}$. Hence, $J_{j,l} = \frac{\rho_j - C_j}{C_j}[\frac{\rho_j - C_j}{C_j}\Delta t_{j,l} + t_l - t_{l-1}]$. It shows that the delay jitter of the lth packet after a k-hop transmission is

$$J'_l = \sum_{j=0}^{k-1} J_{j,l} = [(\frac{\rho_0}{C_0}-1)^2+(\frac{\rho_1}{C_1}-1)^2+...+(\frac{\rho_{k-1}}{C_{k-1}}-1)^2]\Delta t_{k-1,l}+[(\frac{\rho_0}{C_0}-1)+(\frac{\rho_1}{C_1}-1)$$

$$+... + (\frac{\rho_{k-1}}{C_{k-1}} - 1)](t_l - t_{l-1}) \le k(\frac{\rho}{C_{k-1}} - 1)^2\Delta t_{j,l} + k(\frac{\rho}{C_{k-1}} - 1)(t_l - t_{l-1})^2$$

Therefore, the average delay jitter of the flow f in the k-hop non-split transmission is

$$\bar{J}' = \frac{\sum_{l=0}^{p-1} J'_l}{p} \le \frac{k}{p}[(\frac{p}{C_{k-1}} - 1)^2\Delta t_{k-1,p-1} + (\frac{\rho}{C_{k-1}} - 1)(t_l - t_{l-1})].^3 \tag{14}$$

To compare these two average delay jitters, we have

$$\frac{J'}{J} = \frac{C_{m-1}(\frac{\rho}{C_{k-1}} - 1)}{k(\rho - C_{m-1})[t_l - t_{l-1}]}[\frac{k(\frac{\rho}{C_{k-1}} - 1)\Delta t_{k-1,p-1}}{p} + (t_l - t_{l-1})]$$

[1] This inequation is inferred from $\rho_i \le \rho_0 = \rho$ and $C_i \ge C_{m-1}$.

[2] This inequation i inferred from $\rho_j \le \rho_0 \le \rho$, $C_j \ge C_{k-1}$, and $\Delta t_{j,l} \le \Delta t_{k-1,l}$.

[3] This is because $\Delta t_{k-1,l} \le \Delta t_{k-1,p-1}$

$$\approx \frac{C_{m-1}(\frac{\rho}{C_{k-1}}-1)}{k(\rho-C_{m-1})(t_l-t_{l-1})}[\frac{\Delta_{k-1,p-1}}{p}+(t_l-t_{l-1})]^4$$

$$\approx \frac{C_{m-1}(\frac{\rho}{C_{k-1}}-1)}{pk(\rho-C_{m-1})}[\Delta t_{k-1,p-1}+1]^5 = \frac{\frac{\rho}{C_{k-1}}-1}{\frac{\rho}{C_{m-1}}-1}\frac{\Delta t_{k-1,p-1}}{kp}.$$

In order to develop the above expression further, it is noted that

$$\Delta t_{k-1,p-1} = \sum_{j=0}^{k-1}[\frac{pL}{C_j}+\frac{pL}{\rho_j-C_j}] \geq pL\sum_{j=0}^{k-1}[\frac{1}{C_j}+\frac{1}{\rho_j}] \geq pL\sum_{j=0}^{k-1}[\frac{1}{C+\frac{1}{\rho}}] = \frac{kpL(\rho+C)}{C\rho}.$$

Inputting the above result into the expression of $\frac{J}{J'}$, we have

$$\frac{J}{J'} \leq \frac{\frac{\rho}{C_{m-1}}-1}{\frac{\rho}{C_{k-1}}-1}\frac{C_\rho}{C_\rho+L(\rho+C)} \leq \frac{C_{k-1}}{C_{m-1}}\frac{C_\rho}{C_\rho+L(\rho+C)}. \tag{15}$$

5 Simulation Evaluation

In this section, we use simulations in ns-2 [19] to evaluate video transmission performance with and without the split transmission. In accordance with our theoretical analysis, the simulations observe the following metrics.

5.1 Simulation Metrics

- Worst packet delay (WPD). WPD at the ith receiver is calculated by $D_i = \max\{d_{i,j}, j \in [0, p_i-1]\}$, where $d_{i,j}$ is the delay of the jth packet at the ith receiver and p_i is the total number of packets received by the ith receiver. Then, the worst packet delay for all receivers is calculated by

  $$WPD = \max\{D_i, i \in [0, n-1]\},$$

  where n is the number of receivers in the network.
- Average throughput (AT). From the point of view of the ith receiver, the average throughput is the mean rate with which a video flow arrives at the receiver. That is, $T_i = \frac{\sum_{j=0}^{p_i-1} t_{i,j}}{p_i}$. Hence, the average throughput for all receivers is

  $$AT = \frac{\sum_{i=0}^{n-1} T_i}{n}.$$
- Average delay jitter (ADJ). Denote $J_{i,j}$ is the jth delay jitter at the ith receiver. The average delay jitter at the ith receiver is $ADJ_i = \sum_{j=0}^{p_i-2}\frac{J_{i,j}}{p_i-2}$. Average delay jitter in the network is

  $$ADJ = \frac{\sum_{i=0}^{n-1} ADJ_i}{n}.$$

We implement two groups of simulations to observe the above performance metrics for wireless video communications with and without the split transmission.

[4] This is because $\rho \geq k(\frac{\rho}{C_{k-1}}-1)$.

[5] This is because $\Delta t_{k-1,p-1} \geq t_l - t_{l-1}$.

5.2 Simulation I: Single Receiver

This group of simulations is implemented based on the network topology shown in Fig. 2. There are two mobile nodes (s and r) in the wireless network. s is the traffic sender and r is the traffic receiver. The two mobile nodes have an identical set of four radio interfaces and each interface has one channel. Among the four channels, one is used as the control channel and the other three are used as data channels. Under the "good" network conditions, s transmits video traffic to r through channel 1. When wireless links become overloaded, s uses more than one channel to transmit the video to r. Wireless communications adopt 802.11 protocol. The bandwidth of data channels is set as 512Kb, 1Mb, and 1.5Mb respectively. Video transmission rate is set as 128Kbit/s. In the simulation, we import disturbance traffic to generate network load.

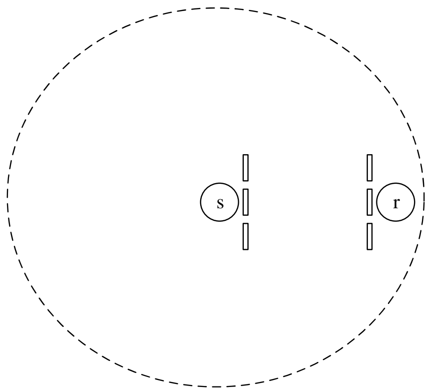

Fig. 2. Network topology for the single receiver simulation.

Fig. 3 presents the worst-case packet delays. The curves show that the split transmission decreases the worst-case packet delays greatly as compared to the video transmission without splitting. It agrees with our theoretical analysis that the split transmission can achieve shorter worst-case delays than the transmission without splitting video. Our analysis in (8) shows that, under the same transmission conditions (e.g. the same C_{min} and C_{k-1}), the delay difference between the two types of transmissions decreases when network traffic load increases. The comparison of the two curves in Fig. 3 proves this analysis, since the 3 data channels are used in the simulations. In the practical implementation of the split transmission, the delay improvement of the split transmission in heavy load network conditions can be enhanced by employing better network resources (e.g. channels with high capacities).

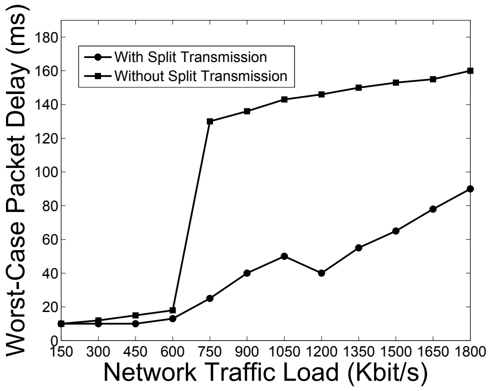

Fig. 3. The worst-case packet delays in the single receiver network shown in Fig.2.

Fig. 4 presents the comparison of the average throughput of video communications with and without split transmissions when the end-to-end delay requirements of video communications are guaranteed. It is observed that the split transmission achieves much higher average throughput than the transmission without splitting video. The throughput advantage of split transmission becomes more obvious when network traffic load becomes heavier. The improved performance is due to dispersing traffic to avoid overloaded channels through multiple non-confliction channels.

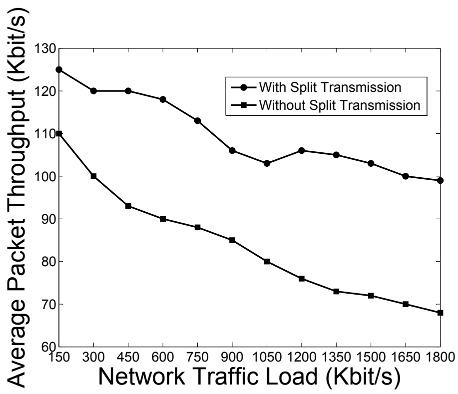

Fig. 4. The average throughput in the single receiver network shown in Fig.2.

Fig. 5 illustrates the average delay jitter performance in this simulation. ADJ increases with the increasing of network traffic load. Traffic controlled by the split transmission suffers from slightly larger ADJ when network traffic load becomes heavy (heavier than 950Kbit/s in our simulation). It is because splitting f into different sub-flows and then transmitting them through different channels causes the variance of the time that sub-flows reach the destination. However, according to [17] and [18], delay jitter within 10ms is acceptable for video flows with the compressed TV quality. It shows that the delay jitter generated by the split transmission is low enough to guarantee continuous and synchronizing reception.

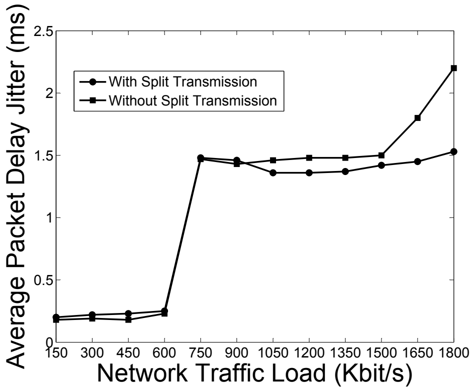

Fig. 5. The average delay jitter in the single receiver network shown in Fig.2.

5.3 Simulation II: Multiple Receivers

The second group of simulations observes the split transmission in a multiple receiver network shown in Fig. 6. There are 25 nodes in the wireless mesh network. These nodes have an identical set of six radio interfaces. Each interface has one channel. Among the 6 channels, two of them are used as control channels, and the other four channels are used as data channels. In the topology, node 0 is the sender. Nodes 8, 11, 12, and 24 are receivers who are randomly selected by the program. Node 0 sends one video flow with the rate of 128Kbit/s to each receiver as shown by the arrowed lines in the figures. Hence, there are 4 video flows in the wireless mesh networks. Wireless communication adopts the 802.11 protocol. Bandwidth of the 4 data channels is set as 512Kb, 1Mb, 1.5Mb, and 2Mb. During the simulations, we import disturbance traffic to generate network load. Under the "good" network status, node 0 sends video flows to the receivers through channel 1. When the network suffers from overload, node 0 employs the split transmission to guarantee the basic layer video transmission.

Fig. 7 gives the worst-case packet delays achieved in the simulations. The figure shows that the split transmission achieves acceptable worst-case packet delays, and also it decreases packet transmission delays greatly when network traffic load becomes heavy (heavier than 144Kbit/s in the simulation) through employing different multiple channels to transmit video. Please note that the

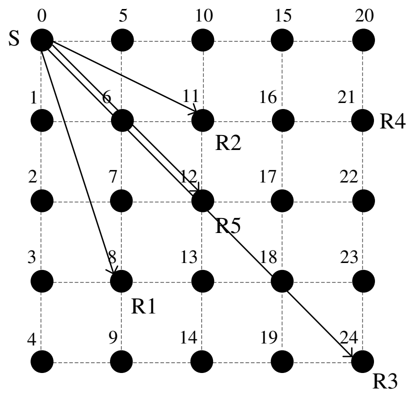

Fig. 6. Network topology for the multiple receiver simulation.

delays under the network traffic load heavier than 144Kbit/s are not plotted because they are much longer than the correspondingly delays of the communication with the split transmission. If we use the equation $\frac{W\hat{P}D - WPD}{W\hat{P}D}$ to check the improvement of worst-case delays, where $W\hat{P}D$ and WPD are the worst-case packet delays achieved without and with the split transmission, the largest worst-case delay improvement of the split transmission is 70% when the network traffic load is 168Kbit/s and the lowest worst-case delay improvement of the split transmission is 5% when the network traffic load is 72Kbit/s. Compared to the single receiver performance, the split transmission works more efficiently in decreasing packet transmission delays in a multiple receiver network. It means that the split transmission controls traffic better in complex network situations.

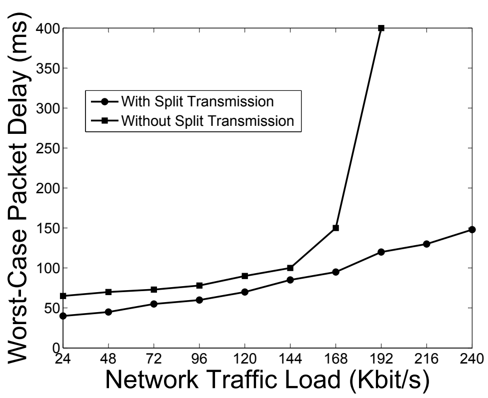

Fig. 7. The worst-case delays in the multiple receiver simulations.

Fig. 8 presents the average throughput curves achieved by the multiple receiver simulations. The split transmission achieves higher average throughput because of avoiding packet loss by using multiple channels. Compared to the performance in the single receiver WMN, the split transmission is more effective in achieving higher throughput in complex network conditions.

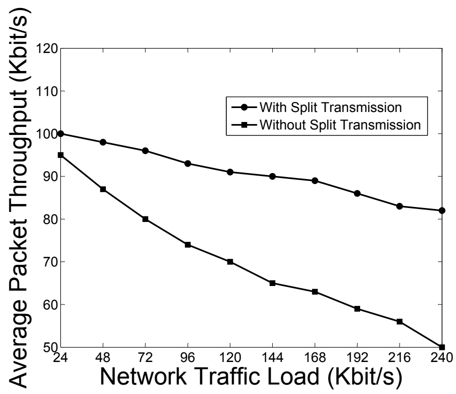

Fig. 8. The average throughput in the multiple receiver simulations.

Fig. 9 illustrates the average delay jitter performance in the multiple receiver network. Similar to Fig. 5, the average delay jitter achieved by with and without the split transmission increases with the increasing of network traffic load. But when network traffic load becomes heavy (heavier than 180Kbit/s in this simulation), the split transmission generates lower delay jitters. Therefore, the split transmission achieves lower delay jitter than the transmission without splitting the video flow when network traffic load becomes heavy. This trend is mainly because, without the split transmission, the heavy network traffic cannot be controlled to generate shorter packet queue and low packet loss rate.

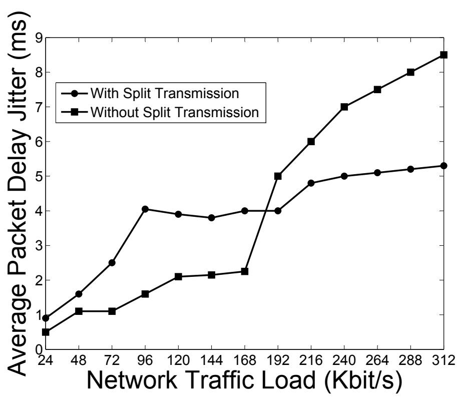

Fig. 9. The average delay jitter in the multiple receiver simulations.

6 Conclusion

In this paper, we theoretically studied the split transmission through the metrics of worst-case delay, average throughput, and average delay jitter in theory. We found that, through using the split transmission, the worst-case delay is decreased to $\frac{\sigma\rho_{k-1}}{LC_{m-1}C_{k-1}}$ of that without using the split transmission; the average throughput is increased to $\frac{1}{1-\prod_{j=0}^{k-1}\alpha_j}$ times of that without using the split transmission; the average delay jitter is $\frac{C_{k-1}C_\rho}{C_{m-1}[C_\rho+L(\rho+C)]}$ of that without using the split transmission. This shows that the split transmission achieves smaller delay, higher throughput, and better continuous wireless multimedia performance. Our simulation evaluation proves our theoretical analysis.

Split transmission has no requirement for underlying network architecture and can be easily developed on top of current wireless hardware and MAC protocols. However it needs multiple radio interfaces at one wireless node and performance improves further if more radio interfaces are available. While the modern technology enables more than one radio interface at each node and is still working on providing more numbers of radio interfaces, split transmission occupies multiple radio interfaces only when network situations become bad. A number of overloaded channels in wireless multimedia communications is caused by short-term burstiness due to the variable rate transmission. Hence, split transmission is very promising to be used currently to achieve high performance wireless multimedia transmission.

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