Delay Modeling for Heterogeneous Backhaul Technologies

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Abstract—With the foreseeable explosive growth of small cell deployment, backhaul has become the next big challenge in the next generation wireless networks in terms of capacity and latency, especially for delay-sensitive services and network functionalities. Heterogeneous backhaul deployment using different wired and wireless technologies may be a potential solution to meet this challenge. Therefore, it is cardinal to evaluate and compare the performance characteristics of various backhaul technologies as a means to understand the effect of backhaul on the total network performance. In this paper, we propose relevant backhaul models and study the delay performance of promising technologies, including fiber, xDSL, millimeter wave (mmWave), and sub-6 GHz, which have different characteristics. Numerical results are presented to show the delay performance characteristics of different backhaul solutions.

I. INTRODUCTION

Densifying the cellular network via deploying ultra dense small cell base stations (BSs) is a promising way to meet the tremendous demand for cellular data towards next generation cellular networks [1]. To carry the traffic from the BSs to the core network and vice versa, the backhaul network needs to be enhanced proportionally. Meanwhile, due to a wider range of services in future cellular networks, low delay on the radio access and backhaul links becomes more and more essential to deliver services, e.g. VoIP and online gaming, with high quality [2]. As a result, backhaul has become the next big challenge to provide reliable and timely connectivity between BSs and core network [3], [4], especially for delay-sensitive services or network functionalities.

Unlike traditional macrocell BSs, which are always directly connected to the operator’s core network through fiber with very low latency or highly reliable microwave links, small cells are not always in easy-to-reach locations, e.g. near street level or lampposts rather than rooftops, which makes traditional fiber or microwave links impractical or cost inefficient. Many wired and wireless technologies have been proposed as backhaul solutions for small cells, and heterogeneous backhaul deployment will be a potential solution [5]–[8]. Wired backhaul systems have the advantages of high reliability, high data rate, and high availability. However, they may sustain long and dynamic delay in the backbone routes or switches due to multiple hops, especially for xDSL which can only reach 200 - 400 meters per single hop [9]. Wireless backhaul can be deployed more easily and at lower cost. Sub-6 GHz wireless backhaul has the advantage of non-line-of-sight (NLOS) transmission, while the large interference in low frequency bands makes the link unreliable and introduces unpredictable delay. Millimeter wave (mmWave) technologies of 60 GHz and 70 - 80 GHz are another potential backhaul solutions, as they offer high capacity and reliability conditioned on line-of-sight (LOS) links. Due to the small carrier wavelength and the possibility of directional beamforming, the links can indeed be modeled as pseudo-wired without interference, which makes them extremely suitable for dense small cell networks [10]. However, multi-hop implementation is needed in the absence of LOS, which causes additional delay. Therefore, it is essential to model and compare the performance of these different types of backhaul technologies as a means to provide guidelines for system design and evaluation of the feasibility of network functionalities that have strict delay requirements on backhaul.

In this paper, delay performances for four promising backhaul technologies are modeled, analyzed and compared. The main contributions are summarized as follows.

- The packet delay in backhaul links is modeled for various technologies, including fiber, xDSL, mmWave and sub-6 GHz, each with distinct transmission characteristics.
- The mean packet delay and delay-limited success probability in backhaul links are analyzed and compared for the above mentioned four technologies. Our results show that fiber is always the best choice, sub-6 GHz and xDSL fit for links with modest length, while mmWave is a very competitive candidate for short links in terms of delay performance.

II. BACKHAUL MODEL

A. Network Model

We consider a cellular network consisting of radio access and backhaul networks, with gateways, hubs, small cell BSs, and users as components, as illustrated in Fig. 1. The locations of the gateways, BSs and users are modeled as independent homogeneous Poisson point processes (PPP), Φg, Φb and Φu of density λg, λb and λu, respectively. The radio access network connects users with small cell BSs through wireless links,
which usually have only one hop. The backhaul network is composed of links connecting small cell BSs with gateways, which may be multi-hop links using various technologies including wired and wireless ones. The backhaul links using different technologies may differ in the number of hops due to different transmission ranges per single hop. Denote the transmission range of the backhaul link as r, which is the distance to guarantee a certain minimum capacity. For instance, the transmission ranges of popular backhaul technologies can be generally ordered as: $r_{fiber} > r_{sub-6GHz} > r_{xDSL} > r_{mmWave}$ [6]. Denote the number of hops along the link as n, which is determined by the link length d as $n = \lceil d/r \rceil$. Let the small cell BS associate with the nearest gateway. The length of a backhaul link follows a Rayleigh distribution with parameter density function (pdf) given by [11]

$$f_D(d) = 2\pi \lambda_g d \exp\left(-\pi \lambda_g d^2\right).$$

The average length of the backhaul link can be obtained as $1/\sqrt{2\pi \lambda_g}$. Therefore, the average number of hops in a backhaul link $\bar{n} (\geq 1)$ can be estimated as [11]

$$\bar{n} \approx \frac{1}{r \sqrt{2\pi \lambda_g}}.$$

### B. Delay Model

In this work, we focus on the packet delay from the gateway to the BS, i.e., the backhaul network in downlink scenario. This packet delay has a significant impact on the queueing delay and end-to-end delay, and it consists of the packet transmission and propagation delays along the link as well as of the processing delay at each node, each part contributing differently for wired or wireless technologies.

- For **wired backhaul**, the packet delay mainly comes from the processing time in the gateway and hubs, which means that the transmission and propagation delays can be ignored due to the relatively large capacity and highly reliable transmission of the wired backhaul.

- For **wireless backhaul**, the packet delay along the link mainly comes from the transmission time in each hop in case of retransmissions, which implies that a decode-and-forward procedure is applied in each hop.

### 1) Delay in Wired Links

In wired scenario, exponential distribution is usually used to model the distribution of the delay in routers or switches [12], [13]. While many measurements indicate that the distribution of the router or switch delay behaves as Gamma distributed or long-/heavy-tailed. Various types of distributions fit under their specific type of routers, including Gaussian, Gamma, Weibull and Pareto distributions [14]–[17]. Therefore, a general but tractable distribution is needed to model the processing delay of the nodes in wired links. In this work, we assume that the processing delay in each hop follows a Gamma distribution with parameters depending on the load, which includes exponential distribution as a special case.

Given the number of hops of the link $n$, the nodes in the backhaul link that a packet has to traverse include a gateway and $n - 1$ hubs. Denote the processing delay in the gateway and the $i$th ($i = 1, \cdots, n-1$) hub as $T_g$ and $T_{h,i}$, respectively. Then, the total backhaul delay for the BS is expressed as

$$T_{bh,wd} = T_g + \sum_{i=1}^{n-1} T_{h,i}$$

where the subscript $wd$ is used to denote wired connections. The processing delay in the gateway depends on the size of the packet and the number of BSs associated with the gateway. We model $T_g$ using the Gamma distribution with parameters depending on the mean number of BSs associated with a gateway, that is,

$$T_g \sim \text{Gamma}\left(\frac{\lambda_b}{\lambda_g}, \kappa_1, a + b\mu\right)$$

where the first and second terms represent the effect of number of connecting nodes and packet size on delay, respectively. $a$, $\mu$ and $\kappa_1$ are constants, representing the processing capability of the nodes, and $b$ is the packet size. Since a chain topology is adopted, there is one ingress and one egress in each hub. The delay in each hub is assumed independent and follows a Gamma distribution with an identical parameter $\kappa_2$.

$$T_{h,i} \sim \text{Gamma}\left(\kappa_2, a + b\mu\right), \ i = 1, \cdots, n-1.$$ 

Therefore, given the number of hops $n$, the total backhaul delay in the wired backhaul follows the Gamma distribution

$$T_{bh,wd} \sim \text{Gamma}\left(\frac{\lambda_b}{\lambda_g} \kappa_1 + (n-1) \kappa_2, a + b\mu\right).$$

### 2) Transmission in Sub–6 GHz Wireless Links

For the sub–6 GHz wireless backhaul case, we assume that a dedicated spectrum with bandwidth of $W_{sub–6GHz}$ is allocated to backhaul links. Setting the receiver at the origin, the received signal power from the transmitter located at $x$ is $P_Y h_x |x|^{-\alpha}$, where $P_Y$ and $\alpha$ are the transmit power of backhaul nodes ($Y = g$ for gateway, = $h$ for hubs) and pathloss exponent, respectively. Here, gateways and hubs are assumed to have the same transmit power to reach the same transmission range. $h_x$ is the small-scale fading (channel gain) and Rayleigh fading with unit mean is considered in this work. An interference-limited scenario is also considered, i.e. the effect of background noise
In [18], the path loss in LOS link with distance in interference-limited network [18]. Applying the fitted model to antennas, which results in a pseudo-wired noise- rather than high frequency also leads to the possibility of directional transmission can reach about 100 - 200 m [18], [19]. However, band, LOS is needed to establish a link, where one hop links. Due to the relatively high frequency in the mmWave characteristic of a mmWave link is quite different from sub–6 GHz.  

The wireless transmission (including sub–6 GHz and mmWave) is time slotted and one packet is transmitted in each time slot. The transmission in one hop succeeds if the received SIR is above a threshold θ. Otherwise, the transmission fails and retransmission is required. Considering Gaussian codebooks, the amount of bits that can be transmitted in a single successful transmission is given by 

\[ b = \gamma_{bh,s6} W_{sub–6GHz} \log_2 (1 + \theta) \]  

where \( \gamma_{bh,s6} \) is the time slot length with the subscript s6 representing sub–6 GHz.  

The packet delay in sub–6 GHz backhaul links is the time that is needed to successfully transmit a packet from a gateway to a small cell BS via a sub–6 GHz link.  

3) Transmission in mmWave Links: The propagation characteristic of a mmWave link is quite different from sub–6 GHz links. Due to the relatively high frequency in the mmWave band, LOS is needed to establish a link, where one hop transmission can reach about 100 - 200 m [18], [19]. However, the high frequency also leads to the possibility of directional antennas, which results in a pseudo-wired noise- rather than interference-limited network [18]. Applying the fitted model in [18], the path loss in LOS link with distance \( r \) is given by 

\[ L(dB) = 70 + 20 \log_{10} (r) + \xi, \quad \xi \sim \mathcal{N}(0, \sigma^2) \]  

where \( \xi \) is the shadow fading coefficient, and \( \sigma \) is the standard deviation of shadow fading in dB, which is estimated as 5 [19]. Denote the transmit power plus the antenna gains as \( P_{tx}(dB) \) and the noise power density as \( N_0 \). The transmission in one hop succeeds if the received signal-to-noise ratio (SNR) is larger than \( \theta \), that is, 

\[ P_{tx}(dB) - L(dB) - N_0 W_{mmWave}(dB) \geq \theta(dB) \]  

where \( W_{mmWave} \) is the bandwidth. Retransmission is required when failure occurs.  

The packet delay in mmWave backhaul links is the time that is needed to successfully transmit a packet from a gateway to a small cell BS via an mmWave link. If the distance between the small cell BS and the gateway is larger than the one-hop maximum transmission range, the backhaul needs to be deployed with multiple hops, where the total backhaul delay is the summation of delay in the multiple hops when a decode-and-forward protocol is adopted.  

### III. Packet Delay Analysis  

In this section, we present the main results on the mean packet delay and delay-limited success probability in backhaul links.  

#### A. Mean Packet Delay in Backhaul Links  

The mean packet delay is defined as the time needed for a packet to be successfully transmitted from a gateway to a BS. The results are given by the following propositions.  

1) Wired Backhaul:  

**Proposition 1.** Conditioned on the number of hops \( n \), the conditional mean packet delay in wired backhaul links is given by 

\[ T_{bh,wd} = \left( \frac{\lambda_b}{\lambda_g} \kappa_1 + (n - 1) \kappa_2 \right) (a + b\mu) \]  

The mean packet delay in wired backhaul is given by 

\[ T_{bh,wd} = \left( \frac{\lambda_b}{\lambda_g} \kappa_1 + \left( \frac{1}{r \sqrt{2\lambda_g}} - 1 \right) \kappa_2 \right) (a + b\mu) \]  

**Proof.** (8) can be directly obtained from the expectation of Gamma distribution in (3). Applying the approximation of the mean number of hops of a backhaul link in (2) leads to (9). \( \square \)  

2) Sub–6 GHz Backhaul:  

**Proposition 2.** Given the distance between the BS and its nearest gateway \( d \), the conditional mean packet delay in sub–6 GHz backhaul links is given by 

\[ T_{bh,s6} = \frac{\lambda_b}{\lambda_g} \exp \left( \pi \lambda_g \rho(\alpha, \theta) d^2 \right) \]  

where \( \rho(\alpha, \theta) = \frac{\delta^2}{\sin(\delta \pi)} \) and \( \delta = 2/\alpha \). The mean packet delay in sub–6 GHz backhaul is given by 

\[ T_{bh,s6} = \frac{\lambda_b}{\lambda_g} (1 + \rho(\alpha, \theta)) \]  

**Proof.** See Appendix A. \( \square \)  

3) mmWave Backhaul:  

**Proposition 3.** Given that the number of hops is \( n \) and that each hop has a constant distance \( r \), the conditional mean packet delay in mmWave backhaul links is given by 

\[ T_{bh,mm} = \frac{2n \tau_{bh,mm}}{\lambda_g} \frac{1 + \text{erf} \left( \frac{\theta'(r)}{\sqrt{2\sigma}} \right)}{1 + \text{erf} \left( \frac{\theta'(r)}{\sqrt{2\sigma}} \right)} \]  

where \( \tau_{bh,mm} \) is the time slot length, \( \text{erf} (\cdot) \) is the error function and \( \theta'(r) \) is the function of the path loss in mmWave. The mean packet delay in mmWave backhaul is given by 

\[ T_{bh,mm} = \left( \frac{2 \tau_{bh,mm}}{\lambda_g} \frac{1 + \text{erf} \left( \frac{\theta'(r)}{\sqrt{2\sigma}} \right)}{1 + \text{erf} \left( \frac{\theta'(r)}{\sqrt{2\sigma}} \right)} \right) \]  

**Proof.** See Appendix B. \( \square \)
B. Delay-limited Success Probability

To evaluate the capability of backhaul infrastructure for supporting traffic with delay requirements, we define a key performance metric for delay-sensitive services, coined as delay-limited success probability and denoted by $dp$. The delay-limited success probability is the probability that a packet can be successfully delivered before a certain delay deadline. The allowed delay in the backhaul links is denoted as $t_{bh}$. For time-slotted wireless transmission, the delay requirement can be translated into a time slot constraint. The maximum number of time slots that a packet in a wireless backhaul link can be scheduled and transmitted is given by

$$K_{bh} = \lceil t_{bh}/\tau_{bh} \rceil. \quad (14)$$

1) Wired Backhaul:

**Proposition 4.** Given the number of hops $n$, the delay-limited success probability in the wired backhaul is given by

$$dp_{bh, wd} = \frac{\gamma \left( \frac{\lambda_b}{\lambda_b + \kappa_1} + (n - 1) \kappa_2, \frac{t_{bh}}{a + \delta + \mu} \right)}{\Gamma \left( \frac{\lambda_b}{\lambda_b + \kappa_1} + (n - 1) \kappa_2 \right)} \quad (15)$$

where $\gamma(s, x) = \int_0^x y^{s-1}e^{-y}dyds$ is the incomplete Gamma function and $\Gamma(s) = \int_0^\infty y^{s-1}e^{-y}dy$ is the Euler’s Gamma function.

**Proof.** The probability that a packet is successfully delivered to a BS equals the probability that the packet delay along the link does not exceed the deadline. As the wired backhaul delay follows the gamma distribution, the probability can be directly obtained as

$$P(T_{bh, wd} < t_{bh}) = \frac{\gamma \left( \frac{\lambda_b}{\lambda_b + \kappa_1} + (n - 1) \kappa_2, \frac{t_{bh}}{a + \delta + \mu} \right)}{\Gamma \left( \frac{\lambda_b}{\lambda_b + \kappa_1} + (n - 1) \kappa_2 \right)} \quad (16)$$

which gives the result. \qed

2) Sub–6 GHz Backhaul:

**Proposition 5.** Given that the distance between the BS and the nearest gateway $d$, the delay-limited success probability in sub–6 GHz backhaul is given by

$$dp_{bh, sub} = \sum_{k=1}^{K_{bh}} \left( \begin{array}{l} K_{bh} \\ k \end{array} \right) (-1)^{k+1} \left( \frac{\lambda_b}{\lambda_b} \right)^k \times \exp \left( -k\pi \lambda_b \rho (\alpha, \theta) d^2 \right). \quad (17)$$

**Proof.** See Appendix C. \qed

3) mmWave Backhaul:

**Proposition 6.** Given the number of hops $n$, the delay-limited success probability in mmWave backhaul is given by

$$dp_{bh, mm} = \sum_{k=1}^{K_{bh}} \sum_{m=k}^{K_{bh}} \left( \begin{array}{l} K_{bh} \\ k \end{array} \right) \left( \begin{array}{l} K_{bh} - k \\ m - k \end{array} \right) (-1)^{m-k} \times \left( \frac{\lambda_b}{2\lambda_b} \right)^m \times \exp \left( -k\pi \lambda_b d^2 \right) \times \text{erf} \left( \frac{\theta (r)}{\sqrt{2}\sigma} \right) \quad (18)$$

**Proof.** See Appendix D. \qed

### TABLE I: PARAMETER SETTINGS

<table>
<thead>
<tr>
<th>Parameter Settings</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_b$</td>
<td>$10^{-d}/m^2$</td>
</tr>
<tr>
<td>$\lambda_a$</td>
<td>$10^{-d}/m^2$</td>
</tr>
<tr>
<td>$\rho_{xDSL}$</td>
<td>200 m</td>
</tr>
<tr>
<td>$\rho_{mmWave}$</td>
<td>100 m</td>
</tr>
<tr>
<td>$W_{mmWave}$</td>
<td>200 MHz</td>
</tr>
<tr>
<td>$W_{sub-6GHz}$</td>
<td>40 MHz</td>
</tr>
<tr>
<td>$t_{bh,sub}$</td>
<td>5 us</td>
</tr>
<tr>
<td>$a$</td>
<td>10 us</td>
</tr>
<tr>
<td>$P_{tx}$</td>
<td>30 dBm</td>
</tr>
</tbody>
</table>

Fig. 2. Variations of conditional mean backhaul packet delay with system parameters.

### IV. PERFORMANCE EVALUATION

To evaluate the effect of number of hops and packet size on the backhaul delay performance, we give numerical results of the proposed model in this section. The parameter settings are given in Table 1, where the time slot lengths are set to ensure the same transmission bits in a packet given by (5) for different technologies. One hop is assumed for fiber and sub–6 GHz backhauls as the considered distance between the BS and gateway is not so large.

Fig. 2 presents the mean packet delays under different transmission thresholds (accordingly, packet size) and numbers of hops for the considered four technologies. The following
observations can be obtained from Fig. 2(a).

- The mean packet delay increases with the transmission threshold, due to the increase of the packet size given by (5), which increases the processing delay in wired backhaul or increases the mean number of retransmissions in wireless backhaul.
- The mean packet delay in wired backhaul increases approximately linearly with the transmission threshold, which represents the linear relation with the packet size in the proposed model. However, for wireless backhaul, the mean packet delay increases slightly in the low transmission threshold region but significantly in the high threshold region. This is because in the low transmission threshold region, the wireless backhaul transmits with a success probability approaching approximately 1, therefore the delay only depends on the time slot length and number of hops. While in the high threshold region, the success probability decreases quickly thus the number of retransmissions increases significantly.
- Fiber is always the best choice under the parameter settings, due to its longer reach range and higher transmission reliability. xDSL is better than wireless backhaul in the low and high transmission regions, due to the short processing delay in xDSL and highly unreliable transmission of wireless backhaul, respectively. Sub-6 GHz is more robust than mmWave due to their different characteristics, where the former needs to combat with the interference while the latter needs to combat with the random shadowing.

From Fig. 2(b), where the distance is normalized to the number of hops of mmWave, we can see that the mean packet delay increases linearly with the number of hops for mmWave and xDSL with different ratios, but much faster for sub-6 GHz. This means that although sub-6 GHz has a longer transmission range, the mean packet delay performance is not always better due to its transmission unreliability, especially when the transmission distance is large. When the distance between the BS and gateway is quite short \((n = 1, 2)\), mmWave is a quite competitive candidate technology with the delay a little higher than xDSL and fiber but lower than sub-6 GHz, due to its large bandwidth.

Fig. 3 presents the delay-limited success probabilities of the four backhaul technologies. The success probabilities under different delay requirements are shown in Fig. 3(a), which actually give the cumulative density function of delay. The following observations can be obtained.

- The fiber is always the best choice if one shots for the highest possible delay-limited success probability. Sub-6 GHz is better than mmWave in the low delay regime. This shows the advantage of direct transmission as compared with multi-hop transmission in terms of delay performance.
- Despite its low mean delay as shown in Fig. 2(b), xDSL is not an appropriate technology for backhaul when the delay requirement is strict. Obviously, the delay-limited success probability of sub-6 GHz backhaul increases much slowly as compared with other technologies, due to its transmission unreliability. MmWave outperforms xDSL, because of the less transmission uncertainty of mmWave and high processing delay dynamics of xDSL.

Fig. 3(b) gives the same ranking for the four technologies as in Fig. 3(a). The performance with delay requirement of xDSL is relatively poor when the number of hops is large. The delay-limited success probability of mmWave decreases more quickly with the number of hops as compared with sub-6 GHz technology, and will finally be smaller than sub-6 GHz. This again reveals the drawback of multi-hop transmission when considering the delay performance.

V. CONCLUSIONS

In this paper, four promising backhaul technologies, namely fiber, xDSL, mmWave and sub-6 GHz, are studied and evaluated in terms of delay using a spatial backhaul model. The characteristics of wired and wireless transmissions are then investigated, where the former provides reliable transmission with variable processing delay whereas the transmissions of the latter are unreliable. The results show that fiber is the best choice in terms of delay performance. Meanwhile, direct transmission with sub-6 GHz instead of multi-hop transmission with mmWave or xDSL is preferred under a strict delay requirement, while mmWave is a promising solution for links with short distance. Our proposed model and analysis provide
fundamental understanding and guidelines for efficient deployment of backhaul infrastructure in future cellular networks.

APPENDIX

A. Proof of Proposition 2

Given the distance between the BS and its nearest gateway node, the interfering nodes are outside of the ball centered at the BS with radius \( d \). The transmission success probability in a single transmission attempt is given by [11]

\[ p_{ss, bph} = \exp \left( -\pi k_{bb} \rho (\alpha, \theta) d^2 \right). \tag{19} \]

The mean number of transmissions to successfully deliver the packet is in turn \( 1 / p_{ss, bph} \). Furthermore, the probability that the gateway transmits to this BS in each time slot is given by

\[ p_{sl} = \frac{\lambda_g}{\lambda_b}. \tag{20} \]

Therefore, the mean number of time slots to successfully deliver the packet is \( 1 / (p_{sl}p_{ss, bph}) \), which multiplied by the time slot length gives (10). Taking expectation with respect to the random distance \( d \) leads to (11).

B. Proof of Proposition 3

The probability that a transmission of a single hop in a single time slot succeeds is defined, according to (7), as

\[ p_{bh, mm} = P \left( L \leq P_{tx}(\text{dB}) - \theta(\text{dB}) - N_0 W_{\text{mmWave}}(\text{dB}) \right). \]

Given the hop distance \( r \), the transmission success probability can be obtained from (6) as

\[ p_{bh, mm} = P \left( \xi \leq P_{tx}(\text{dB}) - \theta(\text{dB}) - N_0 W_{\text{mmWave}}(\text{dB}) \right) - 70 - 20 \log_{10}(r) \]

\[ = \frac{1}{2} \left( 1 + \text{erf} \left( \frac{\theta'(r)}{\sqrt{2}\sigma} \right) \right). \tag{21} \]

where \( \text{erf} \cdot (\cdot) \) is the error function and \( \theta'(r) (\text{dB}) = P_{tx}(\text{dB}) - \theta(\text{dB}) - N_0 W_{\text{mmWave}}(\text{dB}) - 70 - 20 \log_{10}(r) \). Therefore, the mean packet delay in each hop is given by \( 1 / (p_{sl}p_{bh, mm}) \). Finally, multiplying by the number of hops and time slot length gives the conditional mean packet delay in mmWave backhaul links as (12). Applying the approximation of the number of hops of a backhaul link in (2) leads to (13).

C. Proof of Proposition 5

Since the probability that the gateway transmits to the BS and the transmission succeeds in a single time slot is \( p_{sl}p_{bh, mm} \), the delay-limited success probability is the probability that in at least one of the \( K_{bh} \) time slots the BS is scheduled and the transmission succeeds, that is,

\[ dp_{bh, s6} = 1 - \left( 1 - p_{sl}p_{bh, mm} \right)^{K_{bh}} \]

\[ = \sum_{k=1}^{K_{bh}} \left( \frac{K_{bh}}{k} \right) (-1)^{k+1} p_{sl}^{k} p_{bh, mm}^{k}. \tag{22} \]

where the second equality follows from the binomial expansion. Substituting (19) into (22) gives the result.

D. Proof of Proposition 6

Given the number of hops \( n \), the probability that the packet is successfully delivered to the BS before the delay deadline equals the probability that in at least \( n \) out of the \( K_{bh} \) time slots the BS is scheduled and the transmissions succeed, that is,

\[ dp_{bh, mm} = \sum_{k=n}^{K_{bh}} \left( \frac{K_{bh}}{k} \right) \left( p_{sl}p_{bh, mm} \right)^{k} (1 - p_{sl}p_{bh, mm})^{K_{bh} - k} \]

\[ = \sum_{k=n}^{K_{bh}} \sum_{m=k}^{K_{bh}} \left( \frac{K_{bh}}{k} \right) \left( \frac{K_{bh} - k}{m - k} \right) (-1)^{m-k} p_{sl}^{m} p_{bh, mm}^{m}. \tag{23} \]

where the second equality follows from the binomial expansion. Substituting (21) into (23) gives the result.

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