An Analytical Model of 6LoWPAN Route-Over Forwarding Practices

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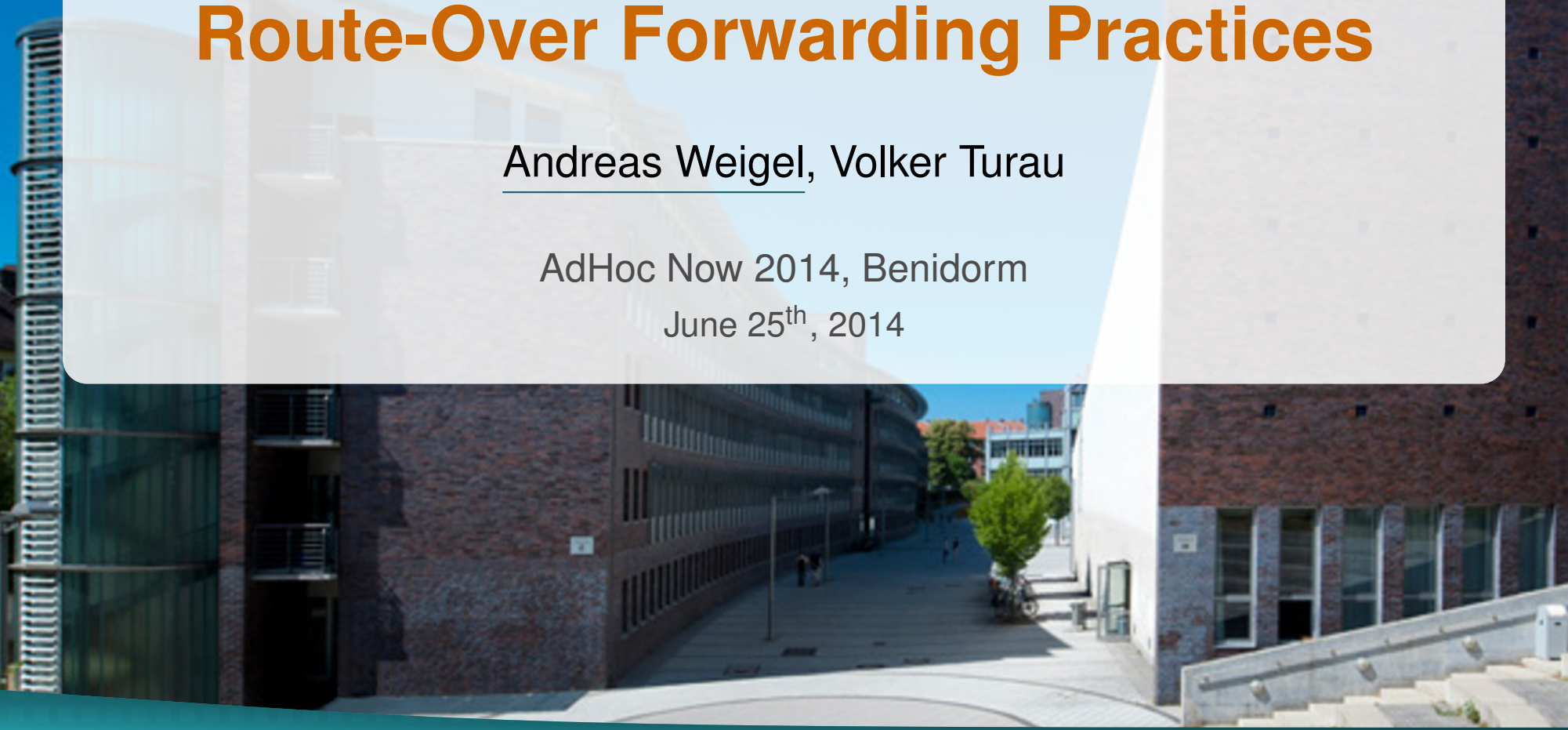

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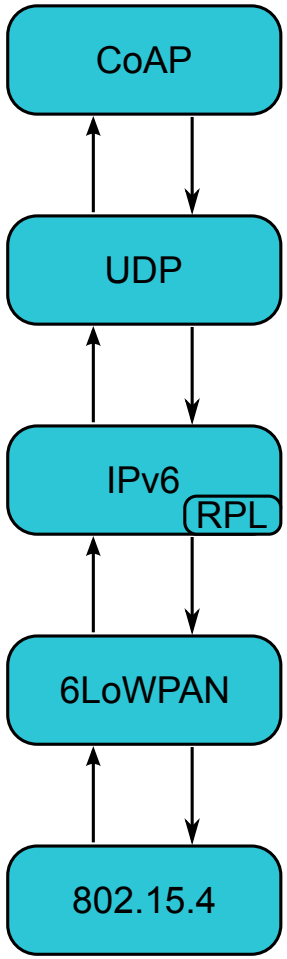
Introduction

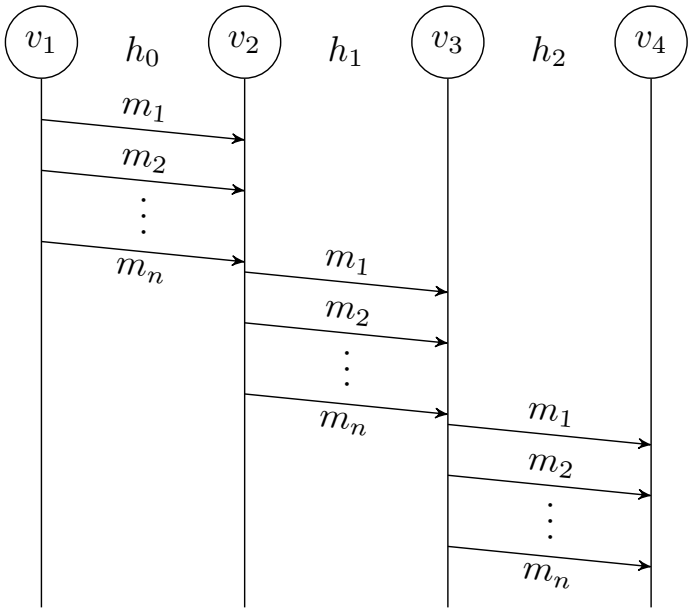
Context

- Vision: "'‘Internet of Things"'
- Standardized protocol stack for Low-Power and Lossy Networks (LLNs)

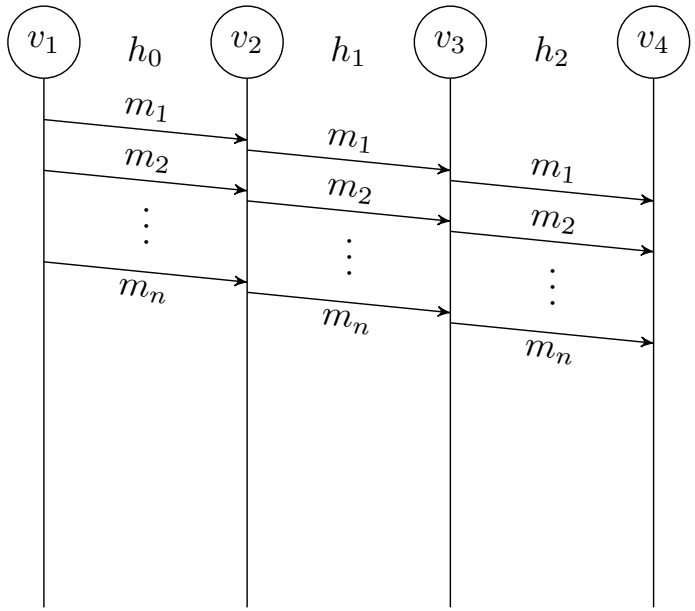
- **6LoWPAN:**
  - compression (headers), **fragmentation** of IPv6 datagrams
  - mesh-under and **route-over** routing



6LoWPAN – Forwarding of Fragmented Datagrams

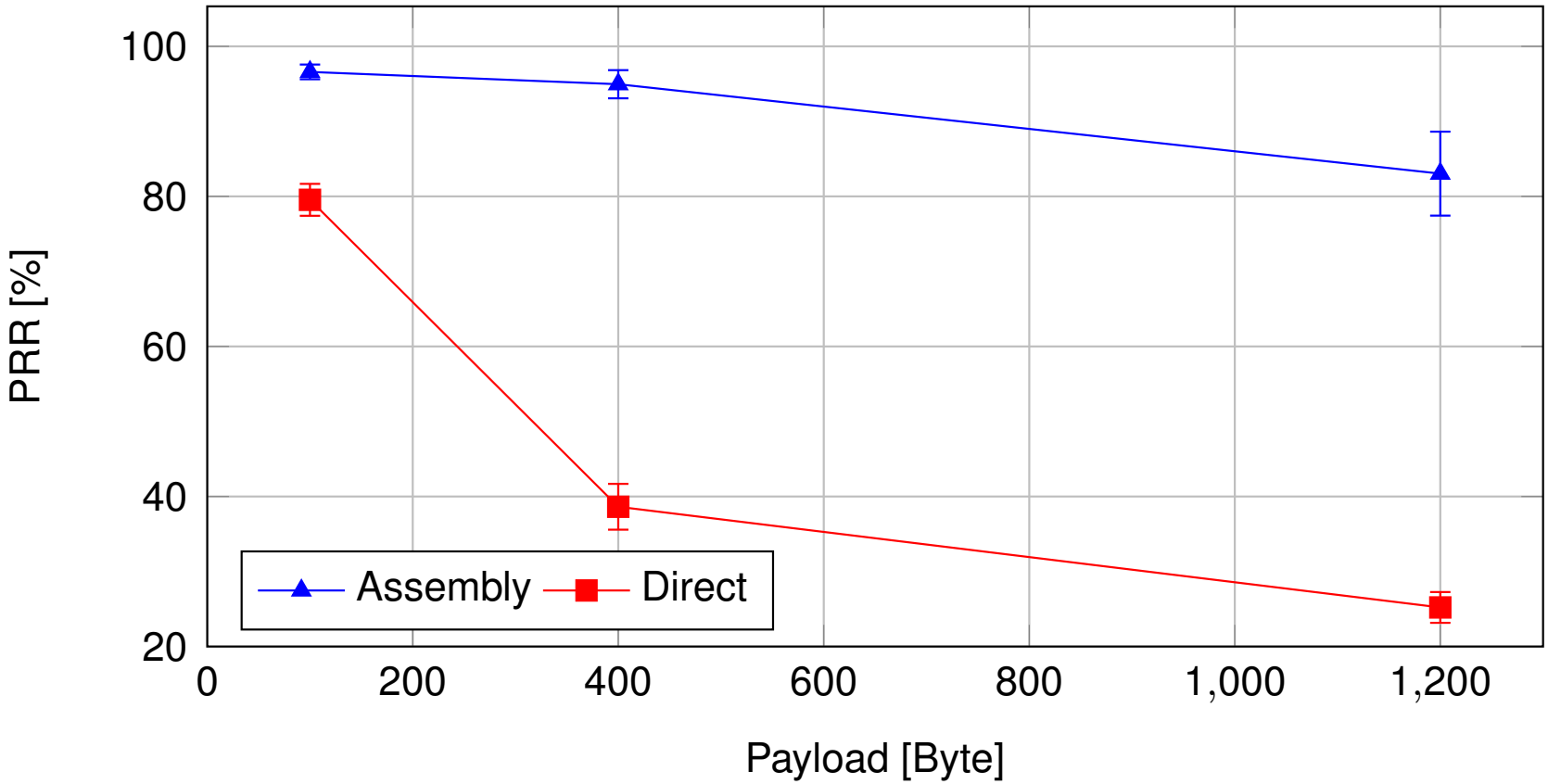


Assembly Mode



Direct Mode

Motivation



⇒ Reason for dramatic results?

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Model

Existing Model (Ayadi et al. - 2011)

Properties

- Based on bit error rate (BER)
- Yields expectation value of number of bits sent
- Additional input parameters: number of fragments, number of hops, correctable bit errors
- Assumes bit errors to be independent
- Persists in sending fragments after loss

$\Rightarrow$ Extend existing model to:

- Adapt to practical forwarding mechanisms
- Quantify overhead due to direct forwarding

Stepwise Model Creation, Link Layer

- Single Transmission (DATA and ACK frame)
  - Based on BER and correctable bit errors (for DATA frame)
  - Probabilities of success, failure, partial failure ($p_{\mathrm{s},k}$, $p_{\mathrm{f},k}$, $p_{\mathrm{p},k}$)
- Link Layer Transmission (including retries)
  - Probabilities of success, failure and partial failure after r retries ($P_{\mathrm{s},k}$, $P_{\mathrm{f},k}$, $P_{\mathrm{p},k}$);
  - Conditional expectation value of number of bits sent in case of success, failure, partial failure and success **or** partial failure ($H_{\mathrm{s},k}$, $H_{\mathrm{f},k}$, $H_{\mathrm{p},k}$, $H_{\mathrm{sp},k}$)
- $P_{\mathrm{s},k} = \sum_{j=1}^{r} p_{\mathrm{s},k}(1 - p_{\mathrm{s},k})^{j-1}$
- $H_{\mathrm{s},k} = \frac{1}{P_{\mathrm{s},k}} \left(\sum_{j=1}^{r} p_{\mathrm{s},k} \sum_{i=0}^{j-1} \binom{j-1}{i} p_{\mathrm{p},k}^{i} p_{\mathrm{f},k}^{j-1-i} (jL_{\mathrm{F}} + (i+1)L_{\mathrm{A}}) \right)$

Stepwise Model Creation, Multi-Hop

- Probabilities of success and failure after passing hops h_0 to h (Q_s, Q_f)
- Corresponding expected number of bits to send (Assembly: E^A, Direct: E^D)

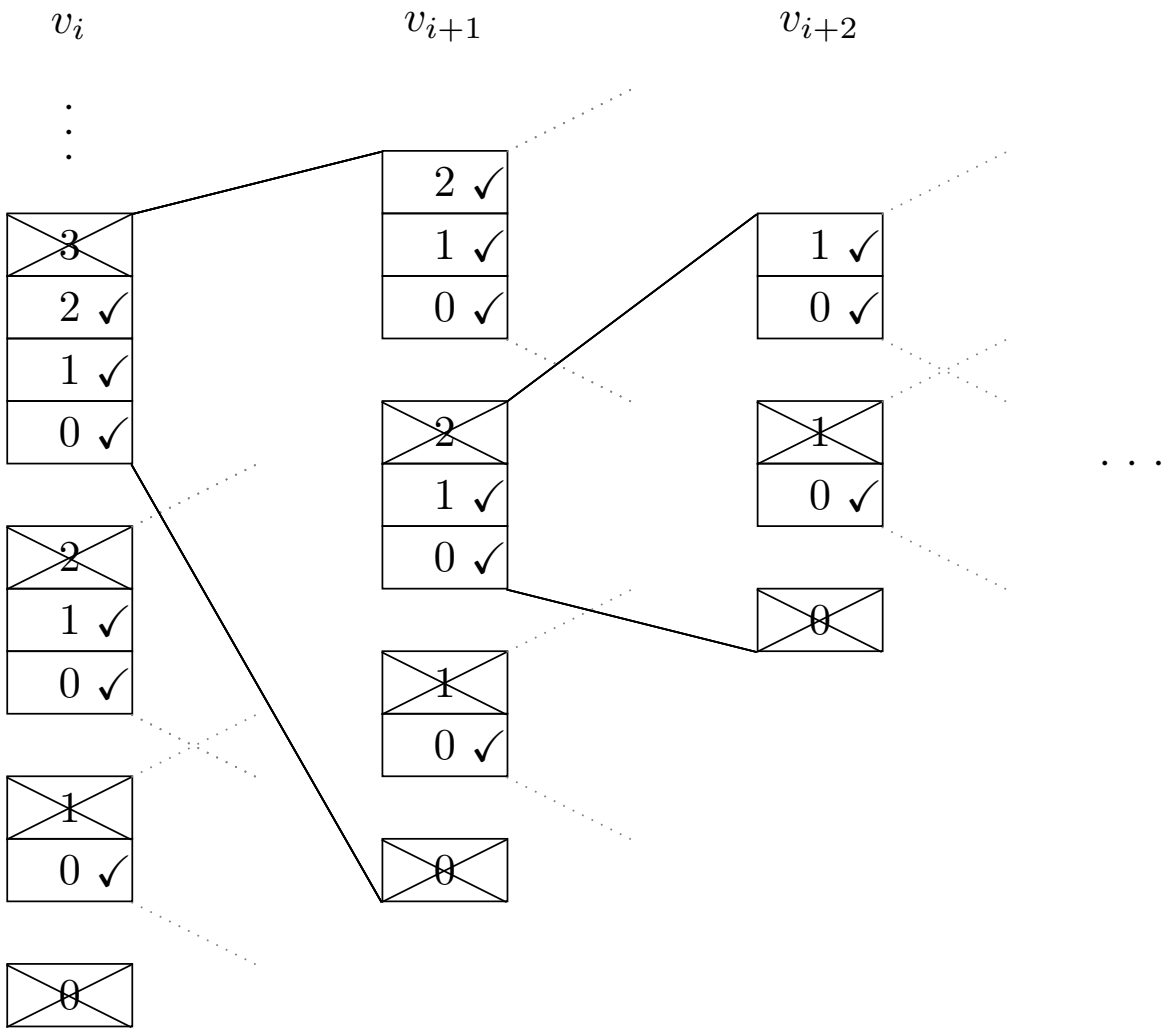
- $Q_\mathrm{s}(h_0, h, m) = \prod_{k=h_0}^{h}(P_{\mathrm{s},k}^{m-1}(P_{\mathrm{s},k} + P_{\mathrm{p},k}))$

Model extension

Different formulas for direct and assembly modes

- Assembly mode: Sender simply gives up at first (partial) failure, no fragments propagated further
- Direct mode: On (partial) failure, already forwarded fragments continue on their path
  - $\Rightarrow$ Recursive formula for expected number of bits to send

Recursive Formula



Recursive Formula (2)

- $E^{\mathrm{D}}(h_0, h, m, H_{\mathrm{acc}}, P) = P \cdot H_{\mathrm{acc}}$ for $h < h_0$ or $m = 0$
- H_{acc}, P: carried-over expected number of bits sent / probability

$$E^{\mathrm{D}} = P \cdot Q_{\mathrm{s}} \left(E_{\mathrm{s}}^{\mathrm{A}} + H_{\mathrm{acc}} \right) + P \sum_{k=h_0}^{h} \left(\sum_{x=1}^{m-1} E^{\mathrm{D}}(k+1, h, x, H_{\mathrm{p}}, Q_{\mathrm{s}}(h_0, k-1, m) P_{\mathrm{s},k}^{x-1} P_{\mathrm{p},k}) + \ldots \right)$$

with

$$H_{\mathrm{p}} = H_{\mathrm{acc}} + (x-1) H_{\mathrm{s},k} + H_{\mathrm{p},k} + E_{\mathrm{s}}^{\mathrm{A}}(h_0, k-1, m)$$

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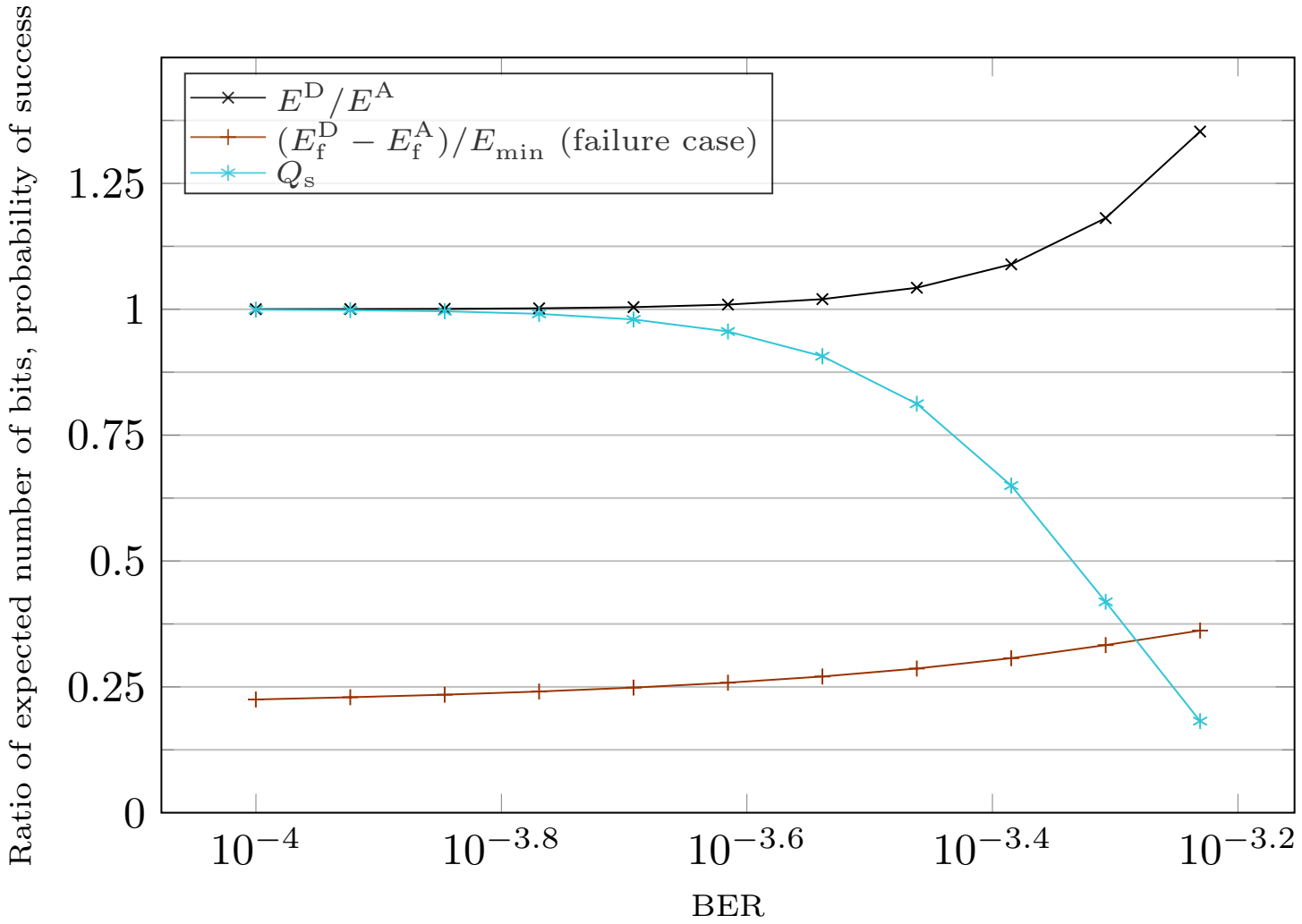
Evaluation

Parameters

r	number of link-layer retries	5
h_0, h	start hop, end hop	1, 8
m	number of fragments	12
BER	bit error rate	variable
L_F	frame size	952 bit
L_A	ack size	56 bit

Direct and Assembly Modes



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Conclusion

Summary & Future Work

Summary

- Extended BER-based model for 6LoWPAN
- Quantified additional bits produced using direct forwarding
- Led to re-evaluation of testbed

Future Work

- Assess impact of effects in testbed experiments
- Implementation efficiency

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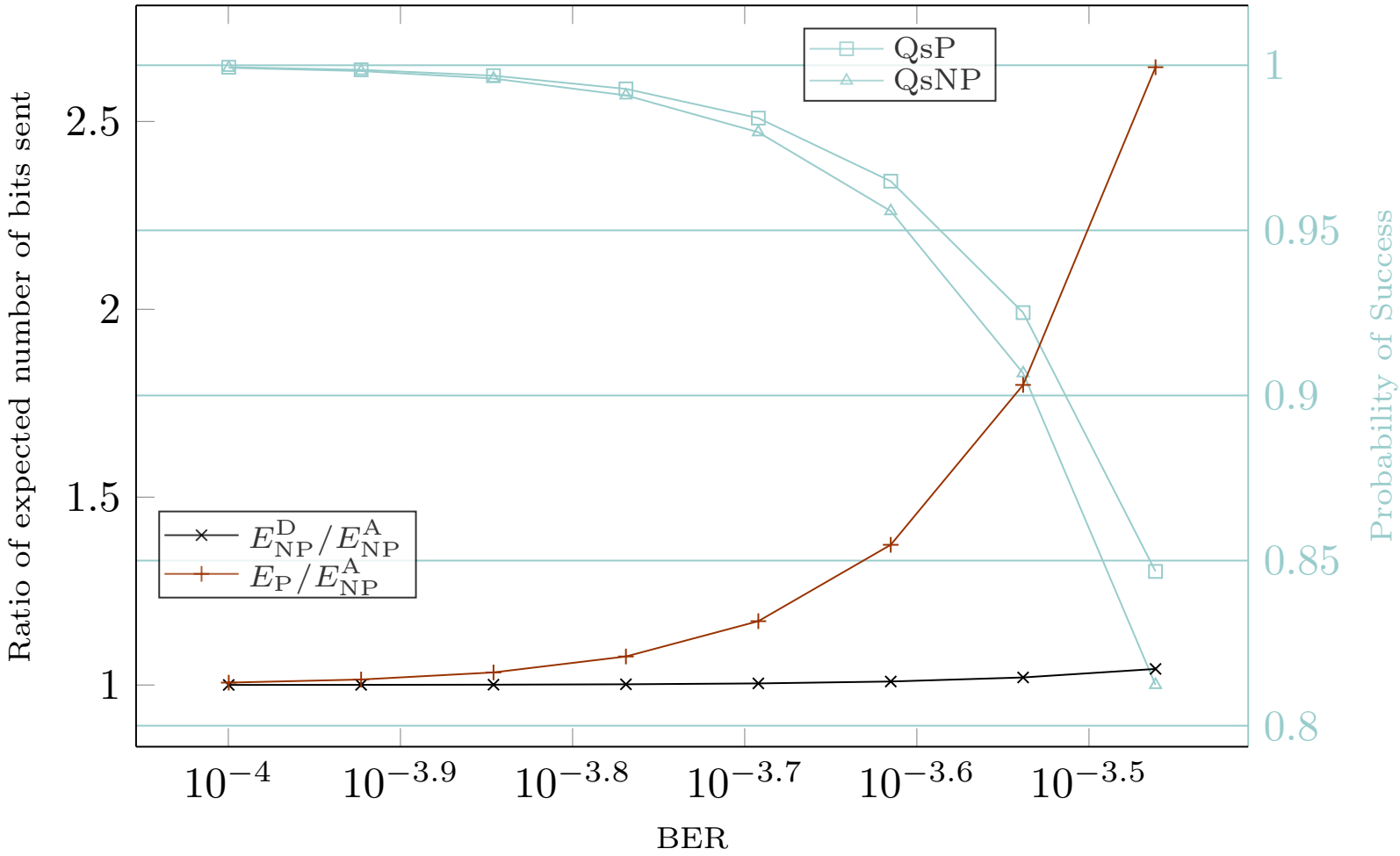
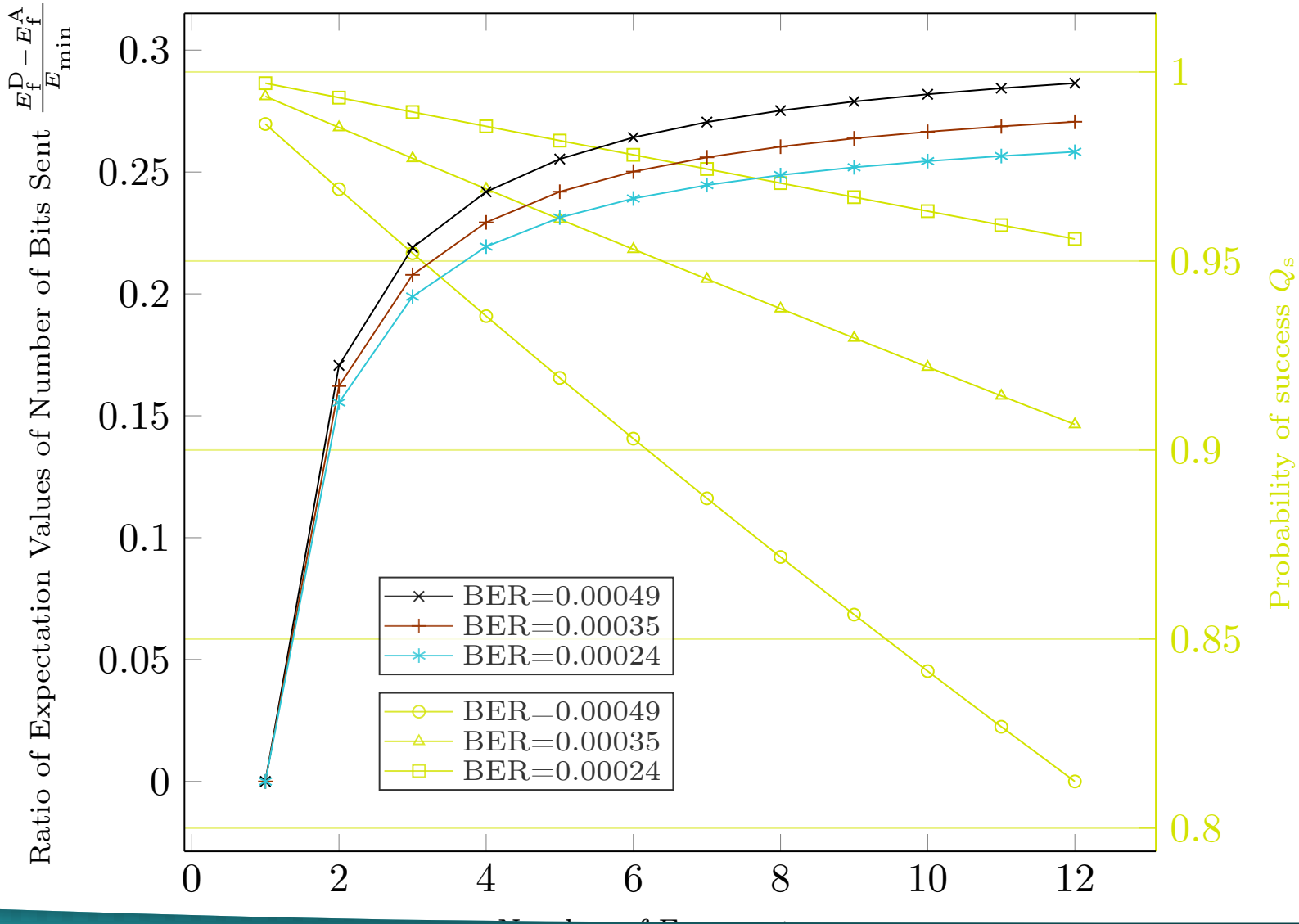
Persistent vs Non-Persistent

NP: non persistent; P: persistent



Variable Number of Fragments



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