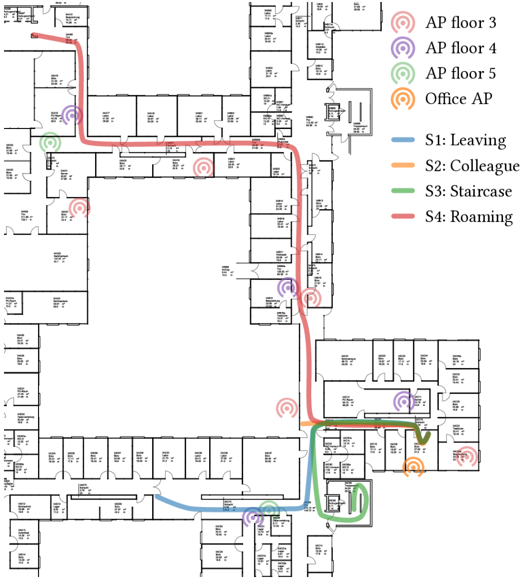
Learning Wi-Fi Connection Loss Predictions for Seamless Vertical Handovers Using Multipath TCP

Jonas Höchst, Artur Sterz,
Alexander Frömmgen, Denny Stohr,
Ralf Steinmetz, Bernd Freisleben

TU Darmstadt and Philipps-Universität Marburg

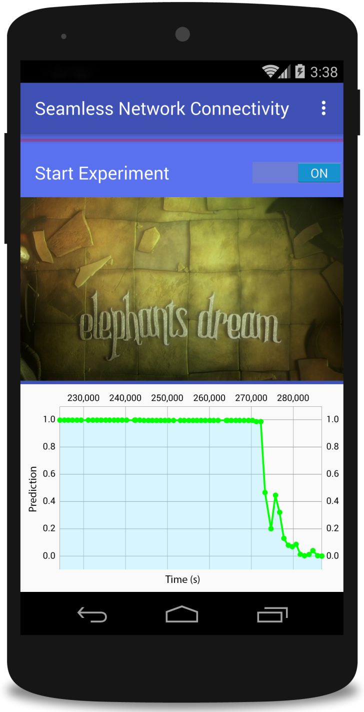


Introduction: Smartphones - Daily Companions

Communication

Information

Entertainment



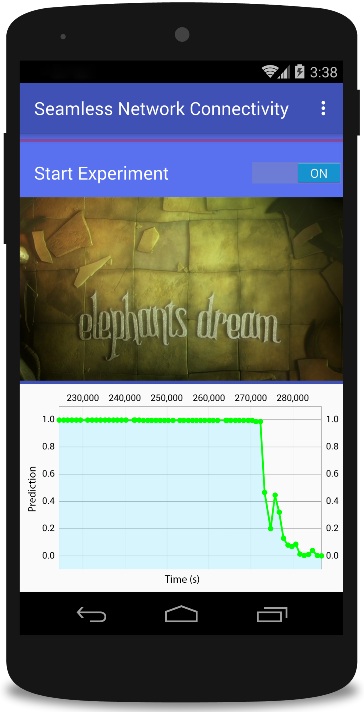
Wi-Fi

Cellular

→ Handover

Introduction: Vertical Handovers Today

- Handovers are performed reactively:
  - Based on weak RSSI or high packet loss
  - Change of default gateway
    - Application has to deal with connection loss



- Multipath-TCP enables seamless handovers
  - Multiple subflows on all available network interfaces
  - Drawback: energy usage, use of limited data plans

Introduction: Contributions

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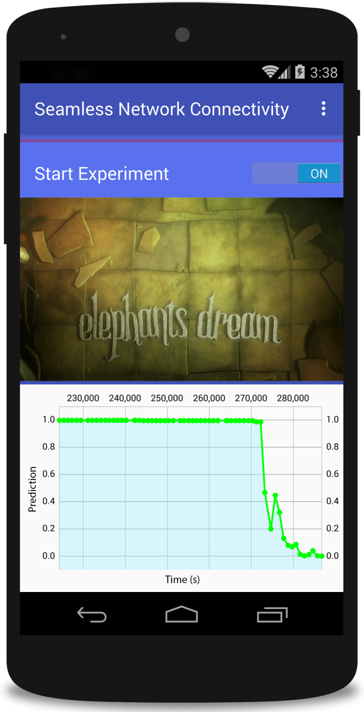
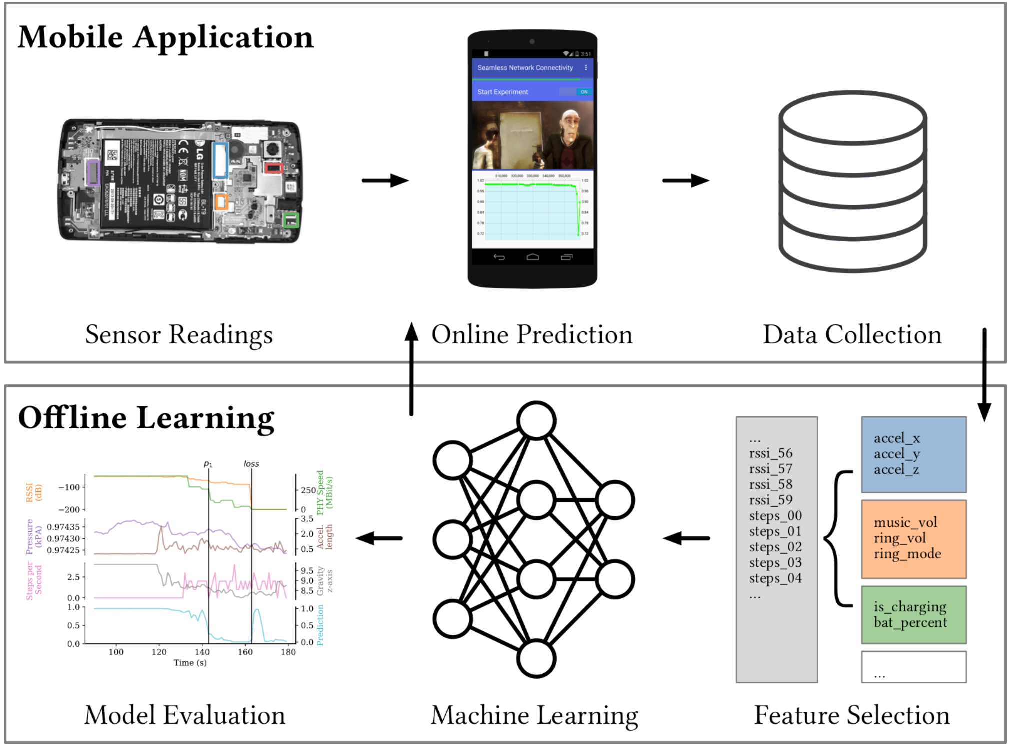
- Novel data-driven, proactive approach for seamless vertical Wi-Fi/cellular handovers
- Multiple heterogeneous smartphone sensors to predict Wi-Fi connection loss
- Multipath-TCP based seamless connection handover
- Experimental evaluation based on Quality of Experience
- Open demo implementation and experimental artifacts



Conceptual Overview



Smartphone Sensor Readings

Wi-Fi Properties

Linear Acceleration

Spatial Orientation

Ringer Mode

Wi-Fi Access Points

Power State

Magnetic Field

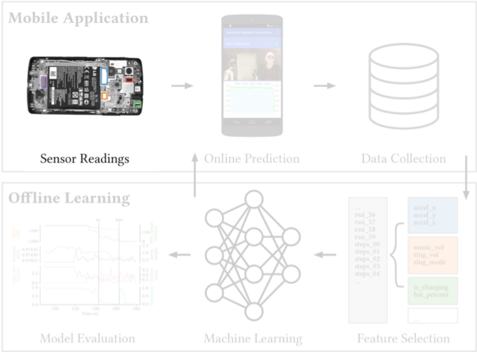
Audio State

Step Counter

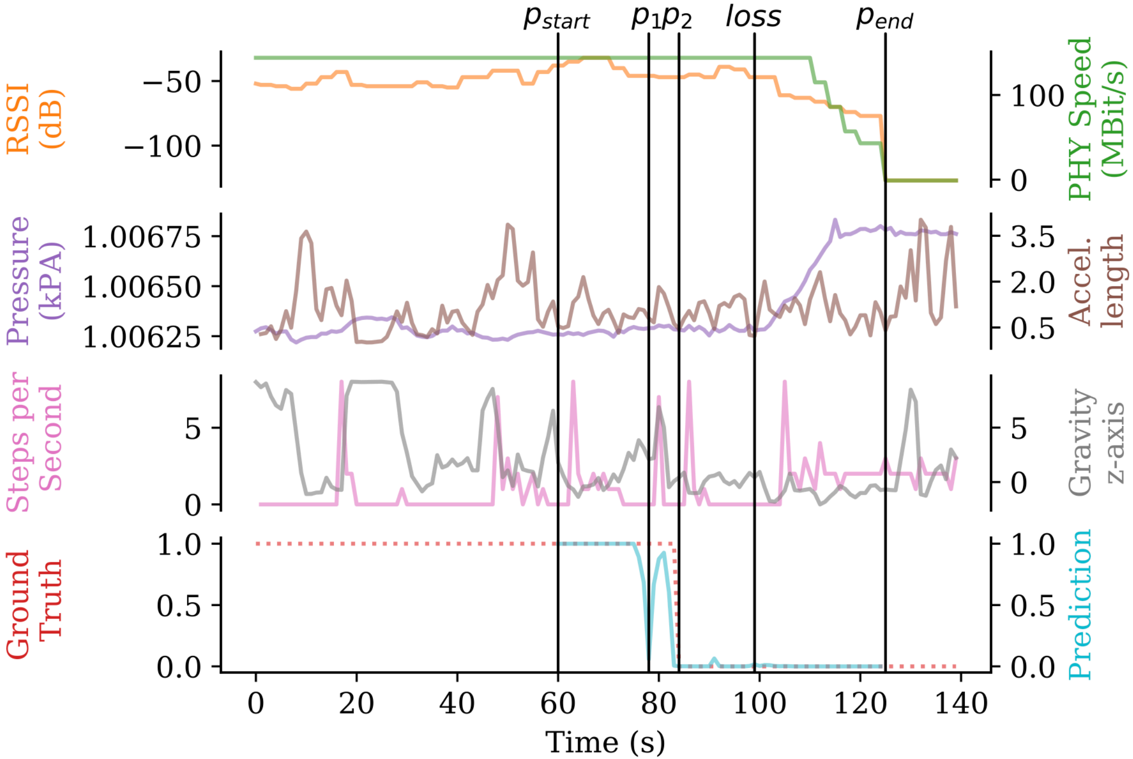
Bluetooth Neighborhood

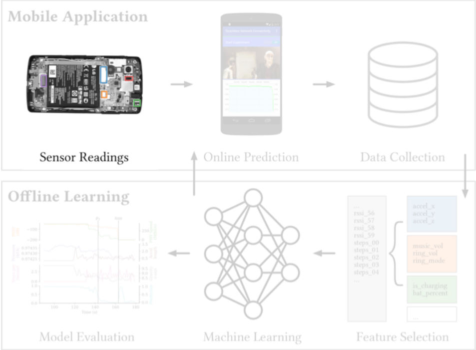
Gravity

Atmospheric Pressure

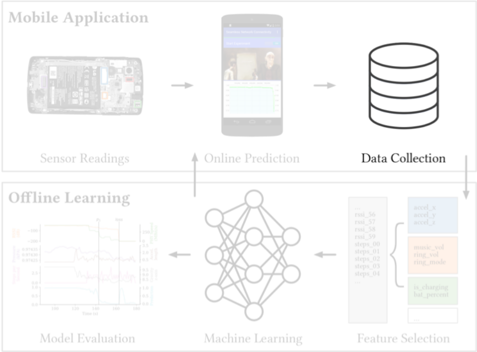


Sensor Data Example



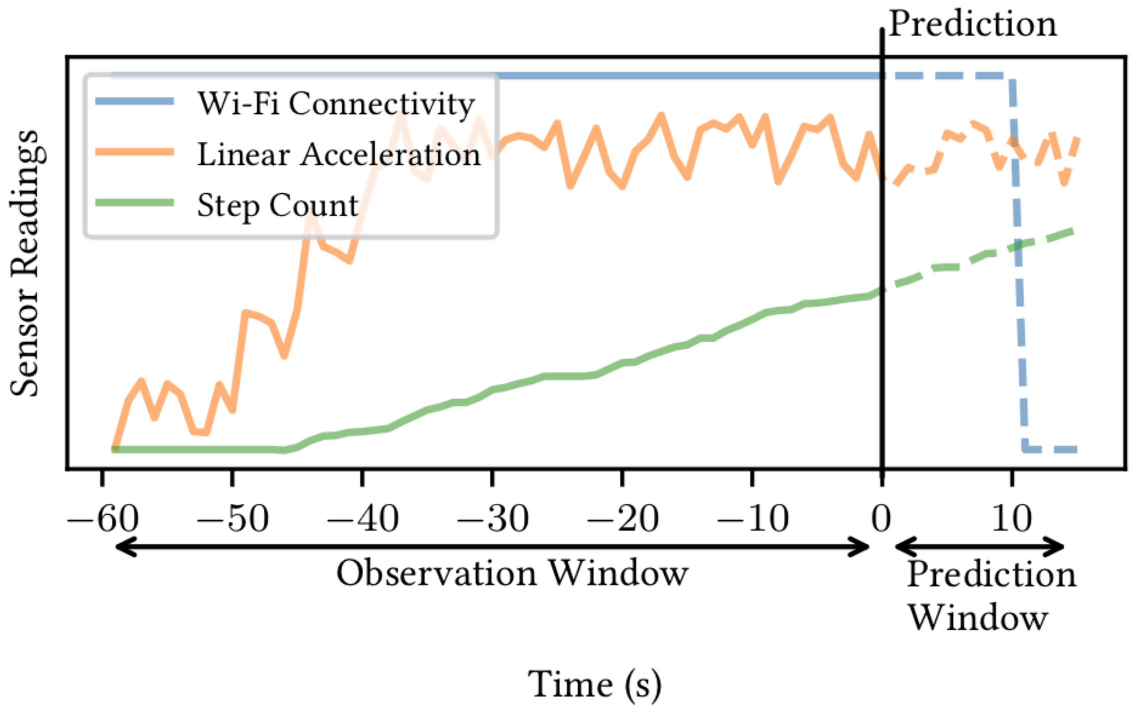


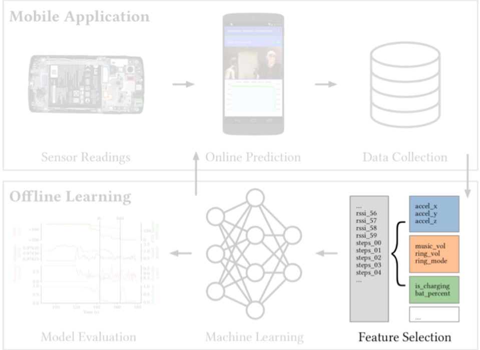
Data Collection



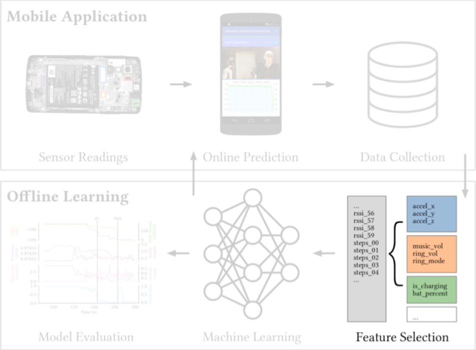
- 20 GB of sensor data from five different users
  - Running for the whole day – daily lives of users
- 900,000 unique samples, collected in three months
- Training and test set
  a) Random split of all available samples (70:30)
  b) User-based split: learn with some users, test with the others

Feature Selection: Observation & Prediction





Feature Selection: Input Vectors



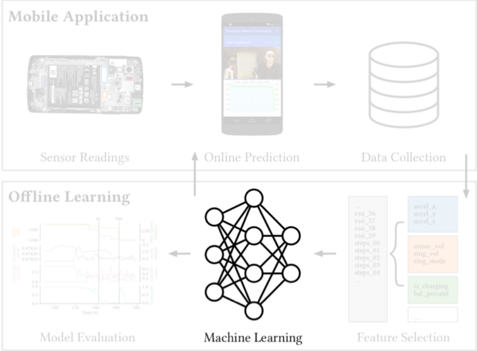
- *Full Feature Vector*
  - All 25 available sensors, 25 x 60 = 1500 features
- *Reduced Feature Vector*
  - Atmospheric pressure, linear acceleration, power, step counter, gravity, Wi-Fi (frequency, speed, RSSI) 8 x 60 = 480 features
- Ground Truth
  - Wi-Fi RSSI > -70 dBm, shifted

Machine Learning: Random Forest

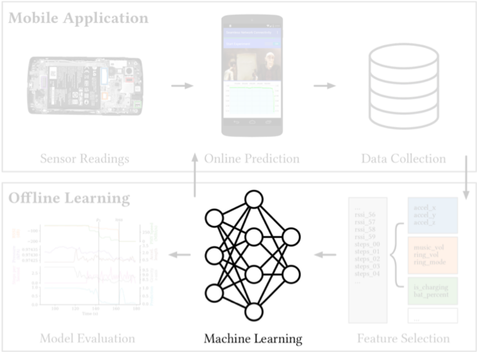
- Requires equally distributed samples: down-sampling, 10 random trees

Event	Prec.	Recall	F_1-score	Support
Loss	**0.86**	**0.98**	**0.91**	52503
No Loss	**1.00**	**0.98**	**0.99**	438772
Total	**0.98**	**0.98**	**0.98**	491275

Table: Random Data Split, Reduced Feature Vector

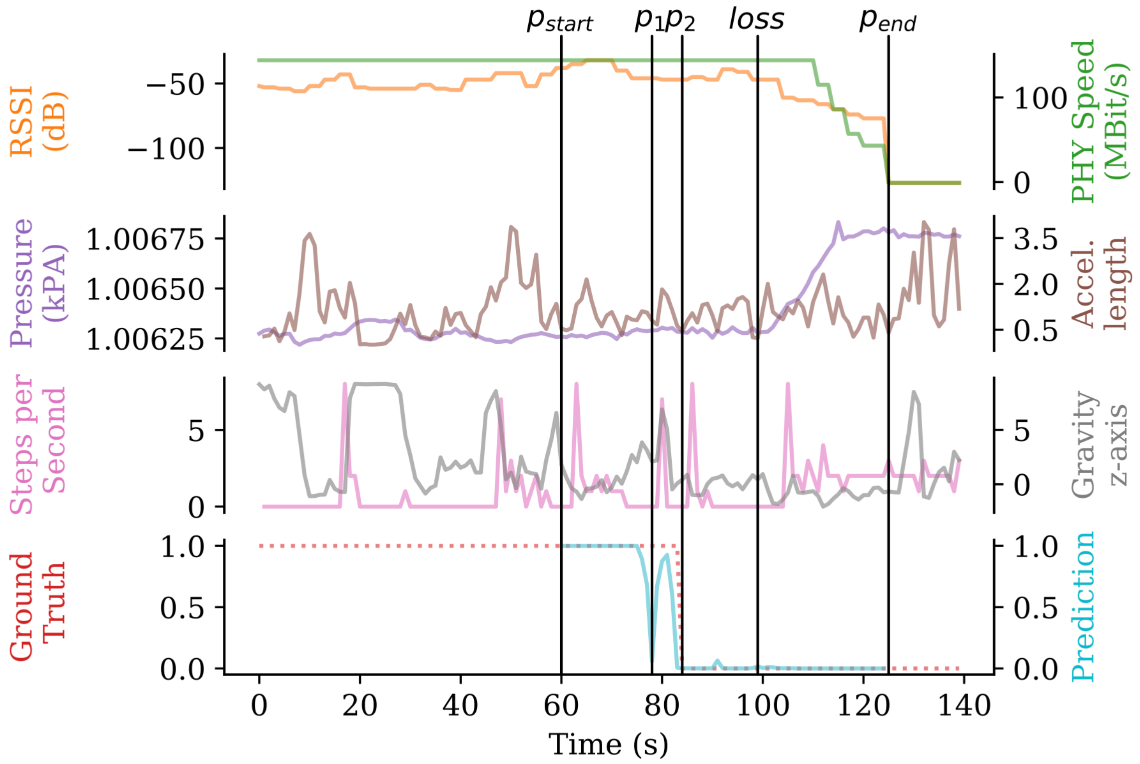


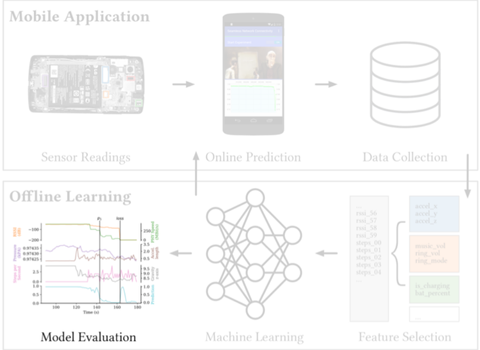
Machine Learning: Neural Networks



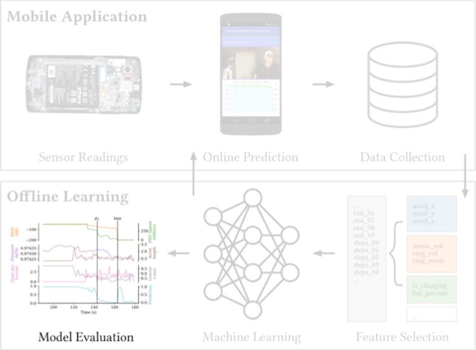
- Input Layer: 60 (only-RSSI) to 1500 neurons, depending on feature vector
- Hidden Layers in different configurations:
  - NN 1: 1 hidden layer of *(100)* neurons
  - NN 2: 3 hidden layers of *(300, 200, 100)*
  - NN 3: 5 hidden layers of *(400, 400, 400, 400, 400)*
- Output Layer: 1 neuron, indicating loss probability

Model Evaluation: Example





Model Evaluation: Random Data Split



Metric	Forest	*NN 1*	*NN 2*	*NN 3*
Loss Prec.	0.89	0.95	0.97	0.97
Loss Recall	0.98	0.94	0.95	0.95
F_1-score	0.93	0.94	0.96	0.96

Table: Reduced Feature Vector, Random Data Split

Online Prediction: Mobile Application

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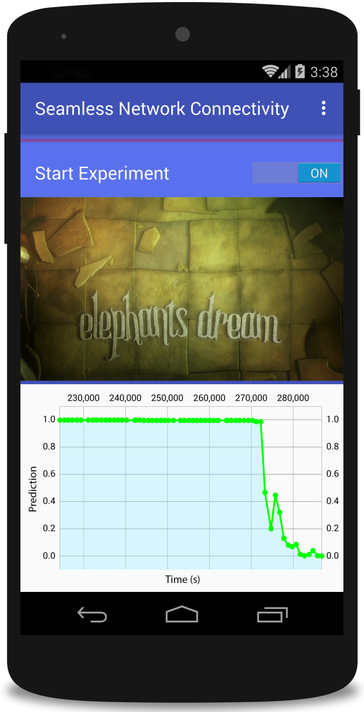
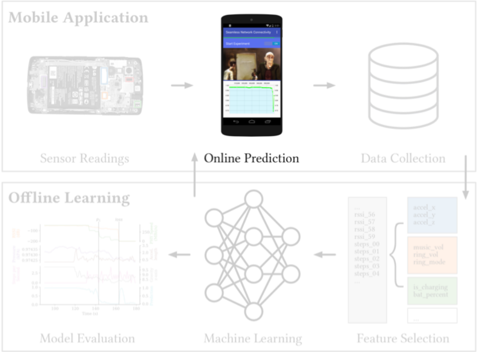
On-Device Model Execution

DASH.js Video Playback

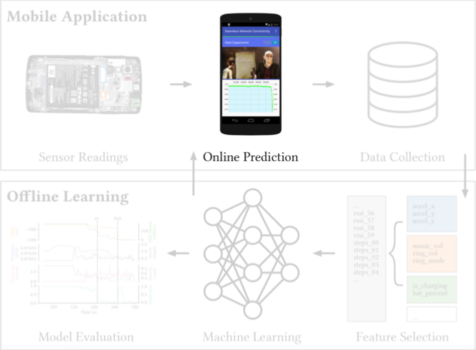
MPTCP Handovers





Online Prediction: DASH.js Video

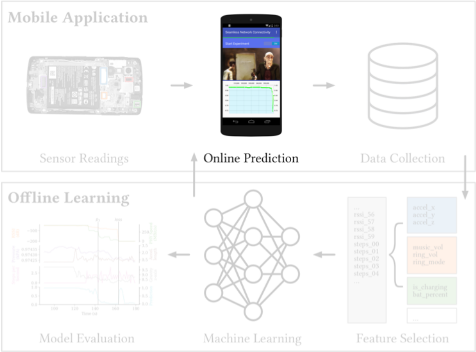
- Dynamic Adaptive Streaming over HTTP(s)
  - Configuration: BOLA adaptation algorithm, 10 s buffer
  - H.264 video, AAC audio
  - Segments of 2 seconds
  - Available bandwidths: 1, 2, and 4 Mbit/s
- Base metrics: Stalls, Bitrate, Adaptations, Buffer levels



Open Movie:
Elephants Dream

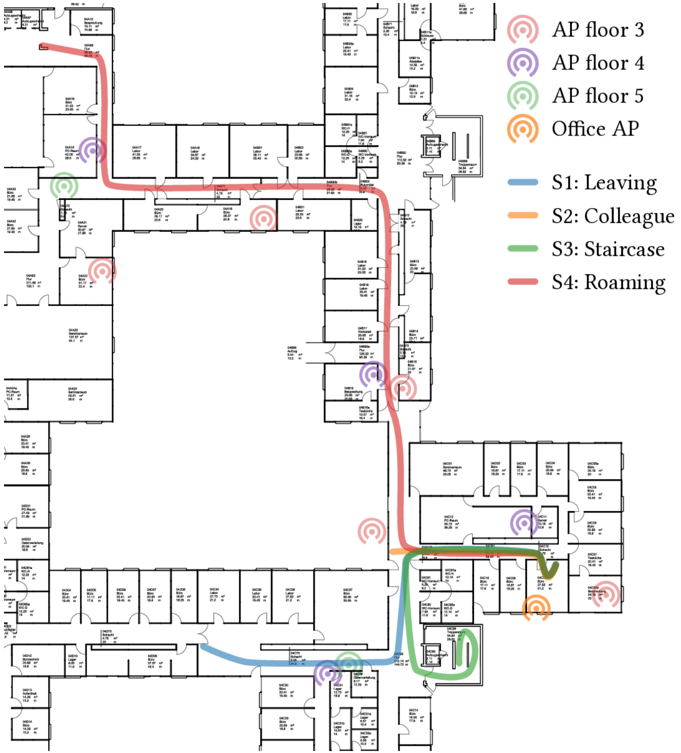
Online Prediction: MPTCP Handovers

- Toggle LTE state based on online prediction
- MPTCP kernel implementation (v0.86) for Android
- MultipathControl (De Coninck et al.)
- Video server: MPTCP v0.92
  - *redundant* scheduler
  - *fullmesh* path manager



Experimental Evaluation: Scenarios

- Four scenarios:
  - Leaving the office (1)
  - Visiting a colleague (2)
  - Using the staircase (3)
  - Wi-Fi roaming support (4)
- Three connectivity modes:
  - Android, MPTCP, Seamless
- Nexus 5, Android 4.4.2



Online Prediction

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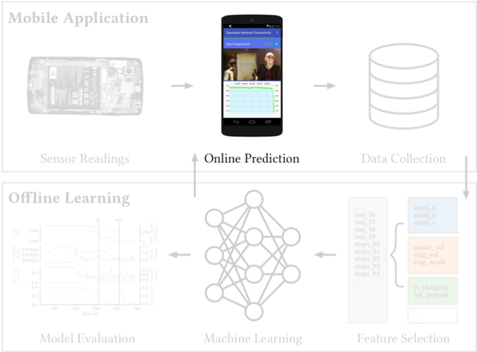
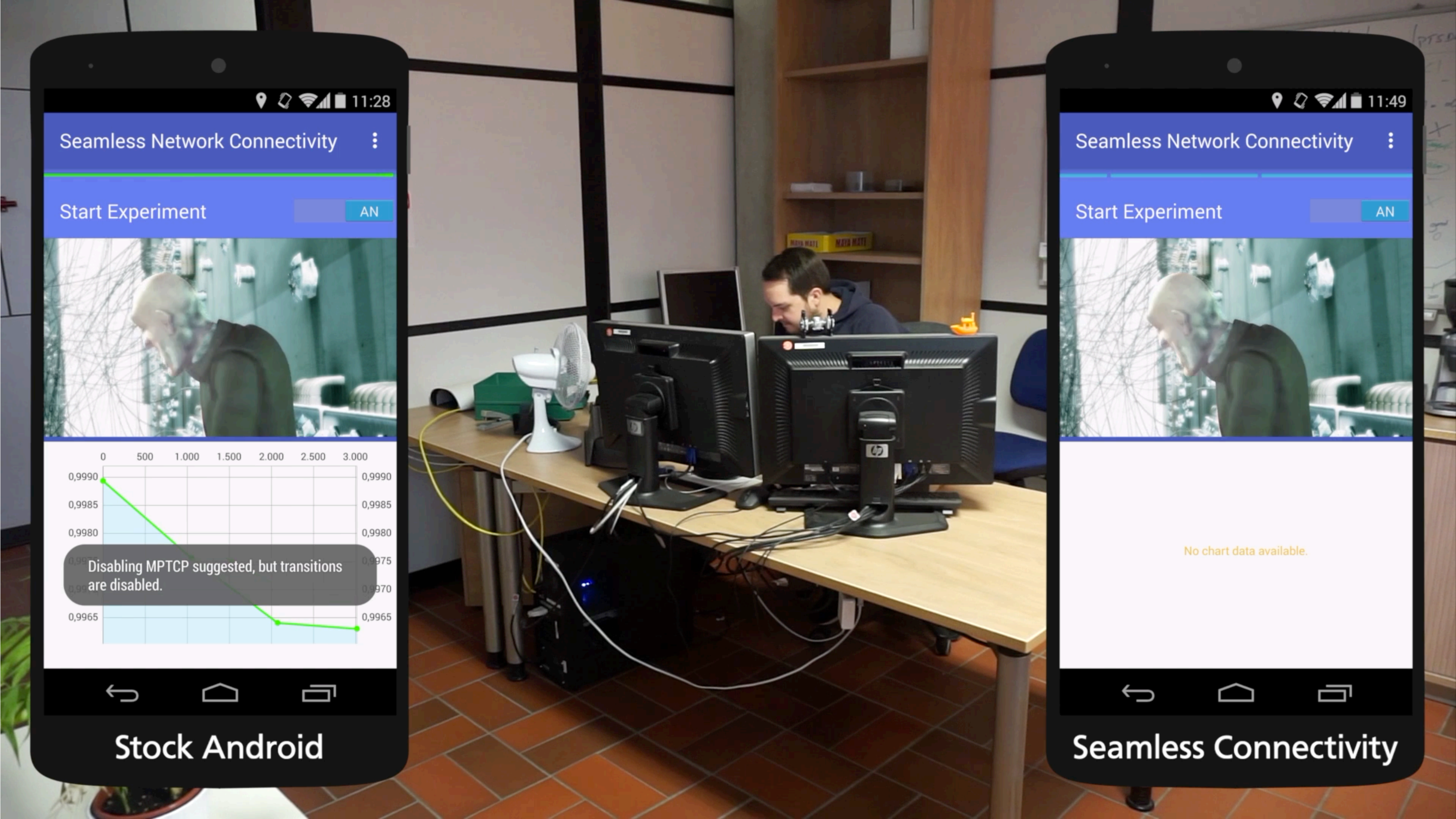


Demo

https://youtu.be/E0CFLk82s6s


11:28
Seamless Network Connectivity
Start Experiment
AN
0
500
1.000
1.500
2.000
2.500
3.000
0,9990
0,9985
0,9980
0,9965
Disabling MPTCP suggested, but transitions are disabled.
Stock Android
11:49
Seamless Network Connectivity
Start Experiment
AN
No chart data available.
Seamless Connectivity

Experimental Evaluation

(a) Scenario 1: Leaving

Mode	# St.	∅ St.	# A.	HQ	∅ TD
Stock	3	1.46 s	23	87 %	21.75 MB
MPTCP	0	0 s	20	89 %	41.32 MB
Seamless	0	0 s	27	88 %	36.11 MB

(b) Scenario 2: Colleague

Mode	# St.	∅ St.	# A.	HQ	∅ TD
Stock	0	0 s	10	92 %	0 MB
MPTCP	0	0 s	10	91 %	9.98 MB
Seamless	0	0 s	17	92 %	9.59 MB

(c) Scenario 3: Staircase

Mode	# St.	∅ St.	# A.	HQ	∅ TD
Stock	3	2.06 s	49	80 %	0 MB
MPTCP	0	0 s	32	87 %	33.92 MB
Seamless	0	0 s	28	85 %	16.81 MB

(d) Scenario 4: Wi-Fi Roaming

Mode	# St.	∅ St.	# A.	HQ	∅ TD
Stock	18	14.98 s	42	53 %	0.89 MB
MPTCP	0	0 s	38	86 %	71.99 MB
Seamless	15	5.47 s	23	84 %	15.50 MB

Overview of Experimental Results

Experimental Evaluation: QoE Results

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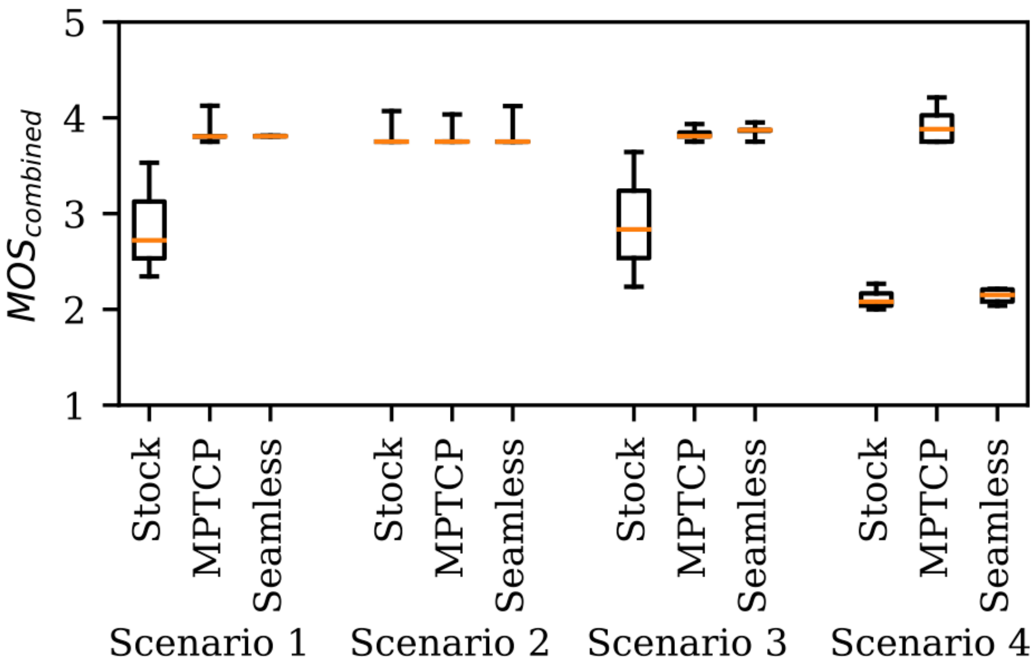


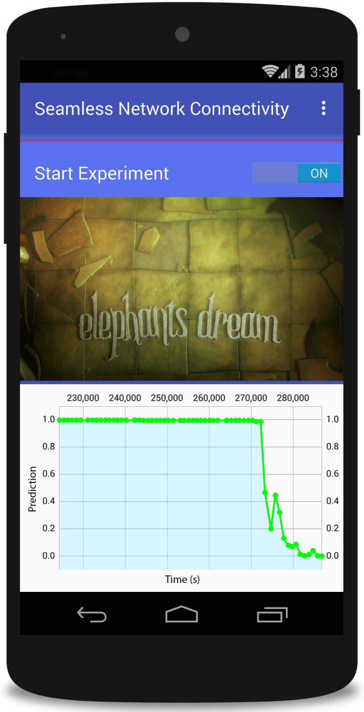
$MOS_{combined}$ values grouped to connectivity modes and scenarios

Conclusion

- Novel data-driven approach for Wi-Fi loss prediction
  - Precision of up to 0.97; Recall of up to 0.98
- Promising results with MPTCP-based handovers
  - QoE improvements of 2.7 to 3.8 in certain scenarios
  - Lower cellular data usage (50%) compared to traditional MPTCP handovers

Future Work

- Enlarge sensor variety: from contextual sensors to domain specific sensors, i.e., to detect high network load
- Online learning on smartphones
  - User-specific models, e.g., user / access point combinations
- Multi-RAT handover predictions (Wi-Fi, 3G, LTE, 5G, …)
- Hardware / low-level implementations
  - Smartphone sensor hub, lightweight neural networks



One more thing…

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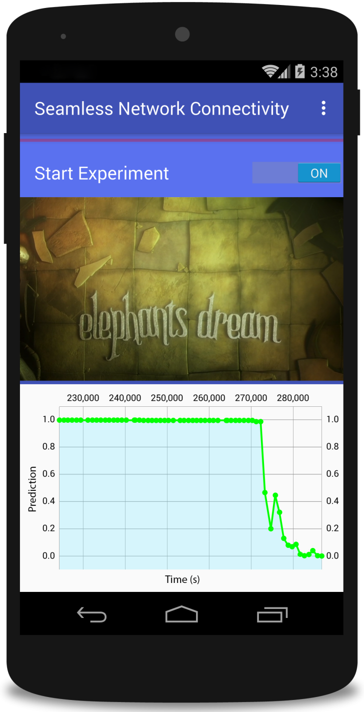

https://umr-ds.github.io/seamcon/

The End

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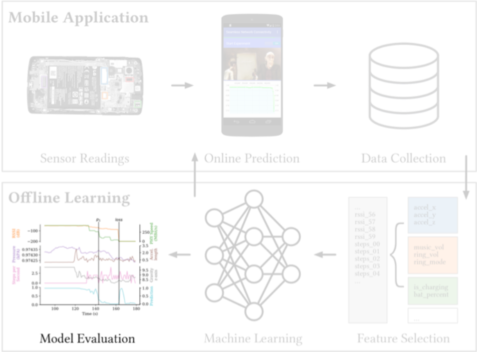
Time for

Questions

Model Evaluation: User-based Data Split



- *Full Feature Vector:* 0.91, 0.72, and 0.68 precision in the Wi-Fi loss class
- *Reduced Feature Vector:* 0.93, 0.92, and 0.79 precision in the Wi-Fi loss class
- Neural networks are capable of predicting Wi-Fi loss.
  - The *Reduced Feature Vector* generalizes better;
  - per-user training significantly improves the results.
- Overall best performance: *NN 3* with the *Reduced Feature Vector*

Experimental Evaluation

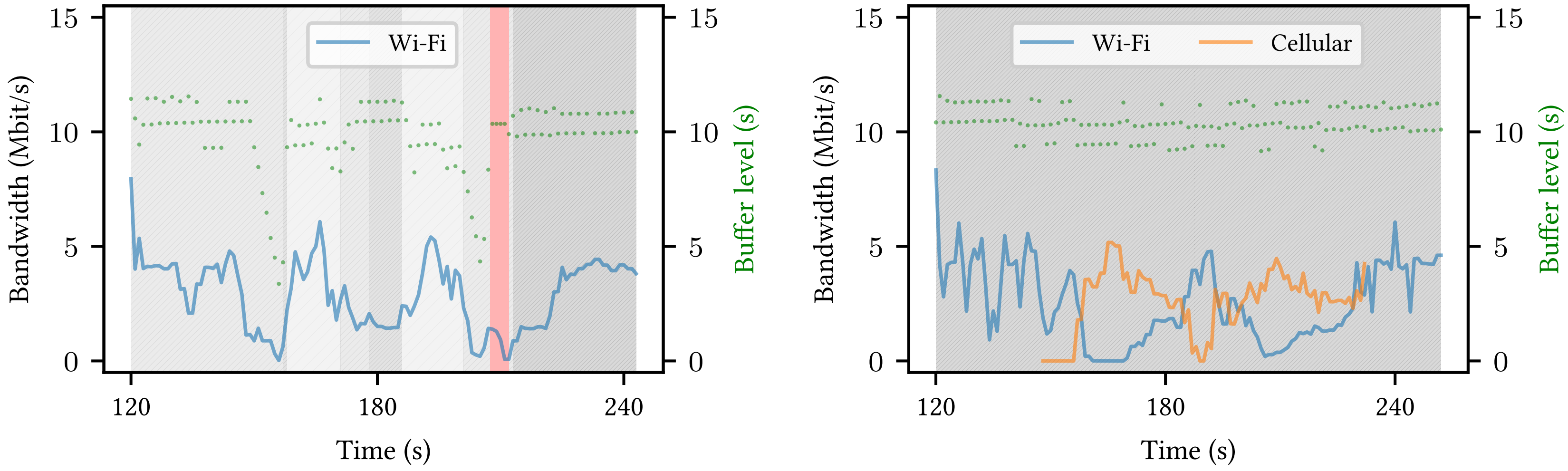
$$MOS_{stall} = 3.5 \times e^{-(0.15 \times L + 0.19) \times N} + 1.5 \qquad (1)$$

$$MOS_{quality} = 0.003 \times e^{0.064 \times t \times 100} + 2.498 \qquad (2)$$

$$MOS_{combined} = \frac{MOS_{stall} + MOS_{quality}}{2} \qquad (3)$$

Mean Opinion Score as QoE Metric

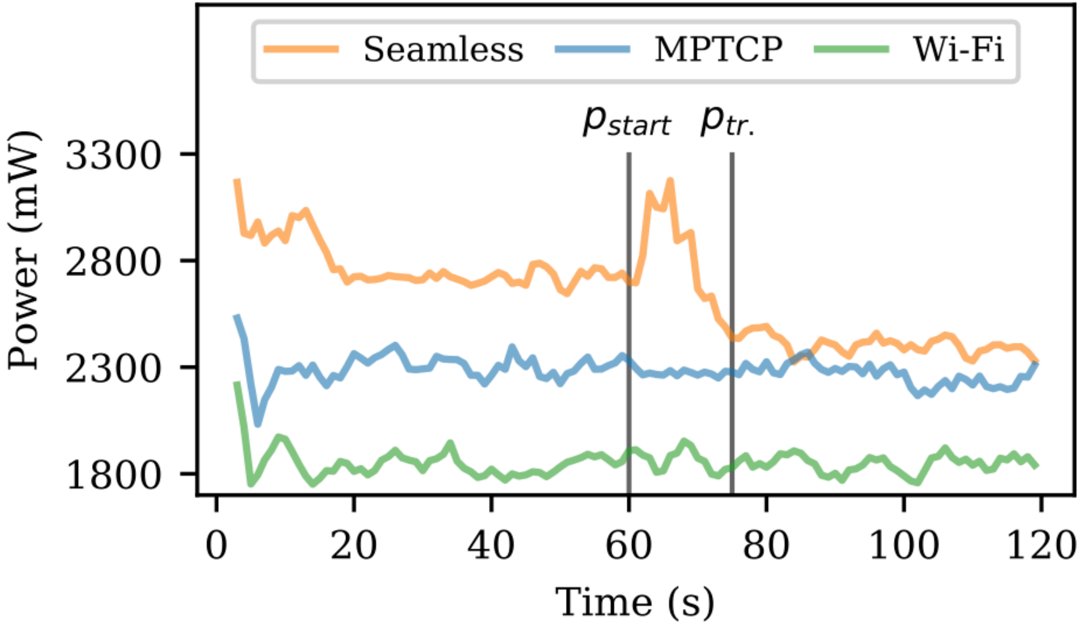
Experimental Evaluation: QoE Results



a) *Stock Android*   b) *Seamless*

Stock and Seamless in Scenario 3

Experimental Evaluation: Power consumption



Power consumption across different connectivity modes