

Table of Contents

Preface	vii
<i>Sergio Barbarossa, Andrea Zanella</i>	
1 Machine Learning, 5G and Beyond Networks: Interplay and Synergies	1
<i>Sergio Barbarossa, Andrea Zanella</i>	
1.1 Introduction	1
1.2 An overview of ML algorithms	3
1.2.1 Supervised learning	3
1.2.2 Unsupervised learning	4
1.2.3 Deep learning	5
1.2.4 Online learning	8
1.3 ML for Wireless Networks	9
1.3.1 ML for physical and MAC layers	9
1.3.2 ML for the network and application layers	11
1.4 Wireless Networks for ML	15
1.5 A perspective on AI-native 6G networks and open challenges	18
2 Model-aided Deep Learning for Future Wireless Networks	29
<i>A. Zappone, M. Di Renzo</i>	
2.1 Introduction	29
2.1.1 State-of-the-art review	30
2.2 Advanced deep learning frameworks	31
2.2.1 Deep unfolding	31
2.2.2 Deep Transfer learning	33
2.3 Model-aided ANN-Based Resource Management	33
2.3.1 Learning to optimize	34
2.3.2 Energy efficiency maximization in interference networks	36
2.3.3 Energy efficiency maximization in dense networks	39
2.4 Conclusions	44
3 How cooperation can boost learning: an overview of Federated Learning	47
<i>F. Busacca, L. Galluccio, S. Palazzo, F. Restuccia</i>	
3.1 Introduction	47
3.2 Distributed Learning	49
3.3 Federated Learning	49
3.4 Use cases	51
3.4.1 Vehicular Networks	52

3.4.2	Spectrum Management	53
3.4.3	Content Caching at the network edge	53
3.4.4	Internet of Things	53
3.5	Challenges in Federated Learning	54
3.5.1	Communication vs Computation	54
3.5.2	Optimal Resource Allocation	55
3.5.3	Privacy and Security	55
3.6	Dealing with Federated Learning limits	56
3.6.1	Network Pruning	56
3.6.2	Weight Quantization	57
3.6.3	Combination of network pruning and weight quantization	57
3.7	Conclusions	58
4	Who Can Learn Best: Distributed AI at the Network Edge	61
	<i>C. F. Chiasserini, F. Malandrino</i>	
4.1	Introduction	61
4.2	Related work	63
4.2.1	Distributed learning	63
4.2.2	Federated learning in edge scenarios	64
4.2.3	Federated learning management	64
4.3	Reference scenario and experiment design	65
4.4	Experiment results	67
4.4.1	Summary and lessons learned	69
4.5	Conclusion	70
5	Decentralized Federated Learning for Extended Sensing in 6G Connected and Automated Vehicles	73
	<i>L. Barbieri, S. Savazzi, M. Nicoli</i>	
5.1	Introduction	73
5.2	Federated Learning in 6G Networks	76
5.3	Decentralized Federated Learning	77
5.4	Vehicular scenario and dataset	80
5.5	Sensors Data Modeling and Processing for Road User Classification	81
5.6	Numerical Results	81
5.6.1	V2X Scenario and System Parameters	83
5.6.2	FL Accuracy in IID V2X scenario	83
5.6.3	FL accuracy in non-IID V2X scenario	84
5.6.4	V2X Signaling Overhead	86
5.7	Conclusions	87
6	Enabling Mobile Edge Intelligence Through Deep Learning Techniques	91
	<i>A. Rago, G. Piro, G. Boggia, P. Dini</i>	
6.1	Introduction	91
6.2	State of the art	93
6.3	Multi-Task Learning at the mobile edge	95
6.3.1	The training dataset	96
6.3.2	Components of the developed MTL model	97

6.3.3	Performance evaluation	98
6.4	Anticipatory resource allocation at the edge	101
6.4.1	System model	102
6.4.2	Optimization problem	103
6.4.3	Mobility prediction model	104
6.4.4	Performance evaluation	105
6.5	Conclusions	107
7	Machine-learning-aided resource allocation in 5G metro networks	113
	<i>L. M. M. Zorello, S. Troia, G. Maier</i>	
7.1	Introduction	113
7.2	Traffic prediction	115
7.2.1	Traffic dataset	116
7.3	Dynamic Optical Routing	117
7.3.1	Phase 1. Offline scheduling	117
7.3.2	Phase 2. Offline planning	118
7.3.3	Phase 3. On-line Routing	119
7.3.4	Results and discussion	119
7.4	Baseband placement optimization in 5G RAN	121
7.4.1	Results and discussion	123
7.5	Final Remarks	125
8	Machine Learning Techniques for Context Extraction and User Profiling in 5G Mobile Systems	129
	<i>Francesca Meneghello, Giovanni Perin, Michele Rossi</i>	
8.1	Introduction	129
8.2	Use case 1 - Passive traffic fingerprinting for user profiling	131
8.2.1	Learning-based fingerprinting architecture	131
8.2.2	Experimental evaluation	133
8.2.3	Possible applications of the fingerprinting engine	134
8.3	Use case 2 - Mobile application classification and service profiling	135
8.3.1	Data collection	135
8.3.2	Supervised learning-based classification	136
8.3.3	Unsupervised learning-based service profiling	137
8.4	Use case 3 - User mobility prediction for network resource management	138
8.4.1	Supervised learning-based mobility prediction	139
8.4.2	Mobility estimates for computing resource management	141
8.4.3	Experimental evaluation	142
8.5	Concluding remarks	143
9	Smart Data Gathering for Network Optimization	147
	<i>Francesco Pase, Federico Mason, Paolo Testolina, Mattia Lecci, Andrea Zanella, Michele Zorzi</i>	
9.1	Introduction	147
9.2	Antenna Design Optimization through Machine Learning	148
9.2.1	Antenna design in mmWave networks	149
9.2.2	Framework Description	150

9.2.3	Example of Use Cases	152
9.2.4	Conclusions	154
9.3	A Multi-Agent Architecture for Flexible Slice Orchestration	154
9.3.1	Related Work	155
9.3.2	Target Scenario	156
9.3.3	Learning Architecture	157
9.3.4	Simulation and Results	158
9.3.5	Conclusions	160
9.4	Federated Learning over Wireless Networks	160
9.4.1	Related Work	160
9.4.2	Problem Formulation	161
9.4.3	Proposed Scheme	162
9.4.4	Simulations and Results	163
9.4.5	Conclusions	164
9.5	Conclusions and outlook	165
10	Wireless Edge Machine Learning in 5G/6G Networks	171
	<i>P. Di Lorenzo, M. Merluzzi, and S. Barbarossa</i>	
10.1	Introduction	171
10.2	Stand-alone edge machine learning:	
	Resource allocation, inference, and training	175
10.2.1	System model	176
10.2.2	Minimum energy under E2E delay and accuracy constraints	179
10.2.3	Best accuracy under energy and E2E delay constraints	182
10.2.4	Numerical results	183
10.3	Cooperative edge machine learning:	
	Resource allocation and federated training	187
10.3.1	System model	188
10.3.2	Mimimum power under E2E delay and learning constraints	192
10.3.3	Numerical results	194
10.4	Conclusions	195