Centralized and Distributed Optimum Power Control and Beam-forming in Network Flooding

Abdelrahman Abdelkader*, Eduard A. Jorswieck*, Marco Zimmerling†
*Communications Laboratory, Faculty of Electrical and Computer Engineering, TU Dresden, Germany
†Networked Embedded Systems Group, Center for Advancing Electronics Dresden, TU Dresden, Germany
{abdelrahman.abdelkader, eduard.jorswieck, marco.zimmerling}@tu-dresden.de

Abstract—**We consider a device-to-device wireless multi-hop communication scenario with resource-constrained devices that require energy-efficient connectivity. Based on the recently proposed Glossy network flooding protocol, we develop both centralized and distributed beam-forming and power control algorithms, and analyze their performance. The proposed schemes are compared in terms of their energy efficiency to the standard Glossy. Numerical simulations demonstrate that a centralized power control scheme can achieve several-fold improvements in energy efficiency over Glossy across a wide spectrum of network configurations at comparable packet reception rates. We also show how power control and beam-forming can be applied in a distributed manner and demonstrate achievable gains compared to standard Glossy. The results indicate that adaptive power control and distributed beam-forming strategies improve energy efficiency, which is one important performance indicator in 5G Internet-of-Things applications.**

I. INTRODUCTION

The development of large-scale wireless networks for internet of things (IoT) and cyber-physical systems (CPS) applications is a clear focus of recent 5G initiatives [1]. Furthermore, the use of wireless sensor and actuator networks in industrial automation is a current trend that has captured the attention of many researchers over the past few years [2]. Requirements of such applications include ultra-responsive connectivity with end-to-end latency on the order of a few milliseconds and high energy efficiency to facilitate long operational lifetimes of embedded battery-powered or energy-harvesting devices. Therefore, more light needs to be shed on low-power wireless networks and their prospects in meeting these requirements.

A. Low-power Wireless Networks

Low-power wireless networking based on the IEEE 802.15.4 standard [3] has received a lot of attention over the last decade, especially in the sensor network community. When operating in the 2.4 GHz ISM band, the standard stipulates a data rate of 250 kbps using offset quadrature phase-shift keying (O-QPSK) with half-sine pulse shaping and direct-sequence spread spectrum (DSSS) in order to match the limited resources available on sensor nodes. Due to the limited communication range of a few tens of meters, the devices collaborate via multi-hop communication. Real deployments of low-power wireless technology range from permafrost monitoring in high alpine regions [4] to closed-loop lighting control in road tunnels [5].

Many low-power wireless applications rely on a common notion of time across nodes (*e.g.*, to correlate sensor readings) and network flooding (*e.g.*, to send a command to all nodes). To this end, Ferrari et al. recently made a significant contribution by proposing the Glossy flooding protocol [6]. As described in Section II, their Glossy protocol provides both fast, reliable one-to-all communication and accurate network-wide time synchronization in multi-hop wireless networks.

The simple, yet disruptive approach of Glossy and the availability of an open-source implementation has arguably created a movement in the low-power wireless networking community, as visible, for example, from the many works building on the basic flooding primitive to improve the performance of stable network functionality, such as in-network processing [7] and data dissemination [8], or to enable entirely new networking abstractions suitable for mission-critical CPS applications [9], [10]. Thus, any innovation at the level of the communication primitive would immediately benefit the many works using it.

In real IEEE 802.15.4 networks consisting of more than 100 nodes, Glossy achieves unparalleled packet failure rates below 10^{-4} and latencies of a few milliseconds, while synchronizing nodes to within sub-microsecond accuracy. As detailed in Section II, Glossy achieves this by using synchronous transmissions of multiple senders and by exploiting constructive interference and capture effects on off-the-shelf hardware.

B. Power Control and Beam-forming

The problem of optimizing transmission power in wireless communications has received a lot of attention due to its potential in allocating resources more efficiently [11]–[14]. The transmit power optimization for the MISO multicast channel is studied in [15], and the joint transmit beam-forming for the dissemination of common information is studied in [11], where a problem formulation is proposed to minimize transmit power under multiple-rate constraints. This problem is shown to be *NP*-hard; however, an approximate solution can be devised using relaxation methods [16]. In [17] the challenges of distributed transmit beam-forming are investigated, where two or more transmitters simultaneously send a common message while controlling their power and phase such that the message is successfully received at a certain receiving node. Several proof-of-concept prototypes are discussed, and their results are summarized. Significant gains in energy efficiency achieved by using distributed transmit beam-forming is accompanied by a trade-off against the implementation overhead [18].

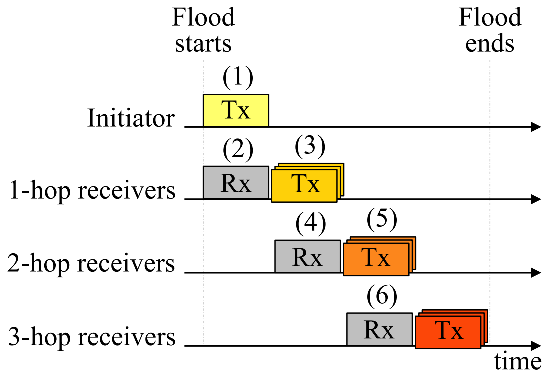


Figure 1: Sequence of synchronous receptions (Rx) and transmissions (Tx) during the flood.

C. Contributions and Road-map

Glossy utilizes no power control, and more importantly, no spatial processing schemes such as distributed beam-forming. This is sub-optimal for the long-term operation of sensor networks (*e.g.*, in monitoring applications [4]) that need energy conservation to assist in elongating their battery life. In this paper, we explore possible advantages of using power control schemes to more efficiently manage network resources and achieve higher energy efficiency in state-of-the-art Glossy.

After describing the basic operation of Glossy in Section II, we conduct in Section III a communication-theoretic analysis, at the most fundamental level, of the state-of-the-art Glossy. Then, in Section IV, we seek to explore and compare different power control and beam-forming schemes with respect to their energy efficiency. We first consider a centralized approach, where a single arbitrator has full nework topology and network-wide channel state information (CSI), and is thus able to make global resource allocating decisions, which we consider to be the upper bound on the achievable performance. We also propose a distributed power control and beam-forming scheme, comparing it against both the centralized approach and standard Glossy in V. Finally, we present our conclusions and agenda for future works in VI.

II. GLOSSY PRIMER

Figure 1 illustrates a Glossy flood in a multi-hop network. A predefined node, the *initiator*, starts the flood by transmitting the packet; all other nodes have their radios turned on (1). Due to the broadcast nature of wireless, all nodes within transmission range of the initiator, the *1-hop receivers*, receive the packet at the same time (2). After a short packet processing delay, the 1-hop receivers re-transmit the *same* packet at the same time (3). Even though these *synchronous transmissions* apparently collide at the *2-hop receivers*, they correctly receive and decode the packet with high probability (4). Then, the 2-hop receivers again re-transmit the same packet synchronously, thereby propagating the flood deeper into the network (5). This way, the flood gradually spreads like a wave and eventually reaches out to all nodes (6). In fact, since each node is allowed to transmit multiple times during the same flood up to a certain *re-transmission limit* N, there are multiple waves, which boosts Glossy's reliability [6].

Unlike prior practical low-power wireless communication schemes, Glossy purposely *forces packet collisions* rather than trying to avoid them (*e.g.*, using carrier sensing or scheduling non-interfering transmissions across individual links). Indeed, to enable successful packet reception, Glossy aligns *identical* wireless signals from multiple concurrent senders within the 0.5 μs bound that allows them to interfere non-destructively using the IEEE 802.15.4 standard [6]. The synchronization of the concurrent senders is established on the fly and in a distributed fashion by using packet receptions during a flood as a reference point. For example, in Figure 1, the simultaneous reception of the packet from the 1-hop receivers in step (4) serves to align the transmissions of the 2-hop receivers in step (5). Glossy achieves this through a careful software design that makes the processing time between reception and transmission as short and deterministic as possible. Glossy also capitalizes on the *capture effect* that lets a receiver demodulate only the strongest of multiple overlapping signals [19].

Due to the combined effect of these phenomena and the diversity gains from applying synchronous transmissions on the network scale, Glossy has been shown to achieve unparalleled packet delivery ratios above 99.99 % in real networks ranging from 26 to 260 nodes in size, from 3 to 8 hops in diameter, from only a few to over 50 nodes in a single broadcast domain, as well as under external interference (*e.g.*, Wi-Fi) and when a large subset of the nodes is mobile [6], [9].

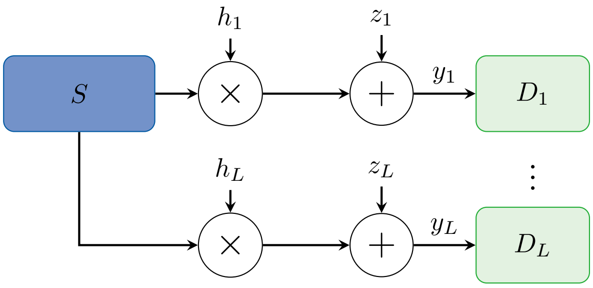
III. SYSTEM MODEL

In order to formulate our power assignment and beam-forming problem, we introduce our communication-theoretic system model and derive expressions for the outage probability of different transmission cases in Glossy. Then, we present the quality of service (QoS) constraints on the achievable rate, which we then use as constraints in our optimization problems.

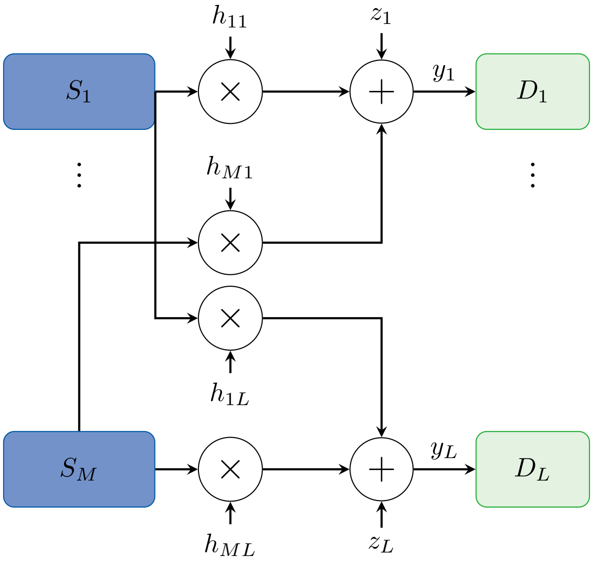
A. Outage Probability

To derive the outage probability, we must separate the different fundamental transmission cases happening within one flood. At the start of a flood, there is one node sending to one or several other nodes. This communication can be modeled as a multicast channel consisting of L point-to-point links as depicted in Figure 2a. During the flood, instead, multiple nodes broadcast the same data to their neighbors: each node receives from several transmitting nodes. This communication can be modeled as a general multicast beamforming channel as depicted in Figure 2b and can be further broken down into L multiple-input-single-output (MISO) channels.

Multicast channel. We start with the multicast channel shown in Figure 2a. Node S transmits a signal x at rate R and nodes $D_1, ..D_l, ..D_L$ receive the signal $y_l = xh_l + z_l$, where z_l is additive white Gaussian noise with $z \sim \mathcal{CN}(0, \sigma_l^2)$, and $h_l \in \mathbb{C}$ is the channel gain from transmitter S to receiver D_l. The channels for low-power wireless devices are typically slow-fading channels. The maximum achievable rate over



(a) Multicast channel consisting of L point-to-point links. Such is the case at the start of any Glossy flood.



(b) General multicast beam-forming channel (multiple transmitters sending the same data) consisting of L multiple input single output (MISO) channels. Such is the case at any intermediate time slot within a Glossy flood.

Figure 2: The basic cases of our communication-theoretic analysis.

these point-to-point channels is upper bounded by the capacity, which is given by [20, Chapter 2]

$$C_{\mathrm{P2P}} = \log_2\left(1 + \frac{|h_l|^2 P}{\sigma_l^2}\right), \tag{1}$$

where $P = \mathrm{E}[x^2]$ is the average transmit power of node S. If S sends at a rate higher than the channel capacity, the reception is not error-free and outage occurs. The outage probability is given by $\Pr(C_{\mathrm{P2P}} < R)$, which is a lower bound on the packet error probability [21].

General multicast beam-forming channel. We turn to the multicast beam-forming case shown in Figure 2b. Each node S_m with $m \in \{1, 2, \ldots, M\}$ simultaneously transmits a signal x_m at rate R and node D_l receive the signal

$$y_l = \sum_{m=1}^{M} x_m h_{ml} + z_l;\ \forall l \in \{1, 2, \ldots, L\} \tag{2}$$

where $h_{ml} \in \mathbb{C}$ is the channel gain between S_m and D_l. In Glossy, all nodes sends the same signal, so $x_1 = \cdots = x_m$. If the transmitters have no channel state information (CSI), the maximum achievable rate R_{MC} is the maximum rate at which node D_l can successfully receive all data transmitted by nodes $S_1, S_2, \ldots, S_M$. This rate is given by [22]

$$R_{\mathrm{MC}} = \log\left(1 + \frac{|\sum_{m=1}^{M} h_{ml}\sqrt{P_m}|^2}{\sigma_l^2}\right), \tag{3}$$

where $P_m = \mathrm{E}[|x_m|^2]$ is average transmit power of node S_m.

IV. GLOSSY MEETS POWER CONTROL AND BEAM-FORMING

There is no doubt that Glossy excels at providing ultra-fast and highly reliable network flooding along with accurate time synchronization [6]. However, in standard Glossy, all nodes transmit with rate $R = 250\,\text{kbps}$ and typically with a power of $0\,\text{dBm}$ [9]; these values correspond to the default and maximum settings as prescribed by the IEEE 802.15.4 standard, respectively. Hence, P_m is a constant value for all $m \in M$ the transmitting set. The corresponding outage probability in this case is $\Pr(R_{\mathrm{MC}}(h_m) < R)$, which is independent of the transmit power P_m. As we will show, this approach performs sub-optimally from an energy point of view and can be further improved by using power control and beam-forming to efficiently allocate power resources which would decrease the energy consumption of the entire network, hence, improving energy efficiency.

To do so, a receiving set of nodes $\mathcal{L}$ has to be established for each transmit node m. The communication range threshold θ is defined such that any node within a distance θ of a transmitting node m is added to the receiving set $\mathcal{L}_m$ of this transmitter. Choosing the value of θ and its effect on the energy efficiency is distinct for each of the following approaches and will be analyzed and discussed thoroughly.

A. Centralized Power Control and Beam-forming

Operation. In order to examine the effect of introducing power control and beam-forming on the energy efficiency of Glossy, we begin with the centralized scheme, which produces global optimum power control and beam-forming decisions. This scheme utilizes the assumption of a central arbitrator having complete channel state information (CSI) across the entire network, and thus, being able to determine the globaly optimum strategy for power assignment and beam-forming. As illustrated in Figure 3 each transmitting node m has a specific transmission range θ in which all non transmitting nodes $l \notin M$ are considered possible receivers. This transmission range is the same for all nodes in the network. In the case of more than one transmitter $M \geq 2$, the global receiving set L includes all nodes within the transmitting range of a transmitter m, as can be seen in Figure 4 where both nodes N_1 and N_2 are transmitting.

Analysis. Let $\boldsymbol{w^H}$ denote the beam-forming weight vector applied to the M transmitters, and let $\boldsymbol{h_l}$ denote the $M \times 1$ complex vector representing the channels from each transmitter to the receiver $l \in \mathcal{L}$. Under the assumption of zero-mean transmit signals with unit variance, the received *SNR* for receiver m is $|\boldsymbol{w^H h_l}|^2/\sigma_l^2$ Therefore, the outage probability expression becomes

$$\Pr\left(|\boldsymbol{w^H h_l}|^2 < (2^R - 1)\sigma_l^2\right) \tag{4}$$

In order to get the constraint for successful reception, *i.e.*, Quality of Service (QoS) constraint, the *normalized channel vector* is defined as $\tilde{\boldsymbol{h_l}} := \boldsymbol{h_l}/\sqrt{(2^R - 1)\sigma_l^2}$ producing

$$\left(|\boldsymbol{w^H}\tilde{\boldsymbol{h_l}}|^2 \geq 1\right) \tag{5}$$

Hence, the power allocation and beam-forming problem aiming at minimizing transmit power, subject to QoS constraints in (5) on all receiving nodes $l \in \mathcal{L}$, can be written as

$$\begin{array}{ll} \text{min} & ||\boldsymbol{w}||^2 \\ \text{subject to} & \left(|\boldsymbol{w^H}\tilde{\boldsymbol{h_l}}|^2 \geq 1\right);\ \forall l \in \mathcal{L} \end{array} \tag{6}$$

Unfortunately, the optimization problem in (6) is a known NP-hard [11]. Therefore, we relax the problem by first, recasting it as follows:

$$\begin{array}{ll} \text{min} & tr\left(\boldsymbol{ww^H}\right) \\ \text{subject to} & tr\left(\tilde{\boldsymbol{h_l}}^H \boldsymbol{ww}^H \tilde{\boldsymbol{h_l}}\right) \geq 1;\ \forall l \in \mathcal{L} \end{array} \tag{7}$$

we make use of the fact that $\tilde{\boldsymbol{h_l}}^H \boldsymbol{W} \tilde{\boldsymbol{h_l}} = tr\left(\tilde{\boldsymbol{h_l}}^H \boldsymbol{W} \tilde{\boldsymbol{h_l}}\right)$ [16] where h_l is the channel gain vector from all M transmitters to receiver $l \in \mathcal{L}$ the receiving set, and $\boldsymbol{W} := \boldsymbol{ww^H}$ is the positive semi-definite transmit covariance matrix of the M distributed transmit nodes. The $M \times M$ matrix $\boldsymbol{W}$ contains the transmit power of each node on the diagonal and the cross-correlation of transmit signals on the non-diagonal. In this way, we reach our goal

$$\begin{array}{ll} \text{minimize} & tr\left(\boldsymbol{W}\right) \\ \text{subject to} & \boldsymbol{h_l W h_l^H} \geq z;\ \forall l \in \mathcal{L} \\ & \boldsymbol{W} \succeq 0 \end{array} \tag{8}$$

where the inequality $\boldsymbol{W} \succeq 0$ means that $\boldsymbol{W}$ is a symmetric positive semidefinite matrix that is greater than or equal to zero in the loewner order. The programming problem in (8) is a convex problem with a linear objective function, convex constraint set and is formulated as explained in [11]. To solve this problem, we use CVX, a Matlab package for solving convex programs [23], [24].

The centralized approach is considered our upper bound on the energy efficiency because a global optimum power allocation decision is made at a central node which possesses network wide CSI. This is a theoretical approach and serves only as a benchmark of comparison to other approaches. For a more realistic approach we introduce in IV-B a distributed power allocation scheme that requires only local CSI, a valid assumption in many networks.

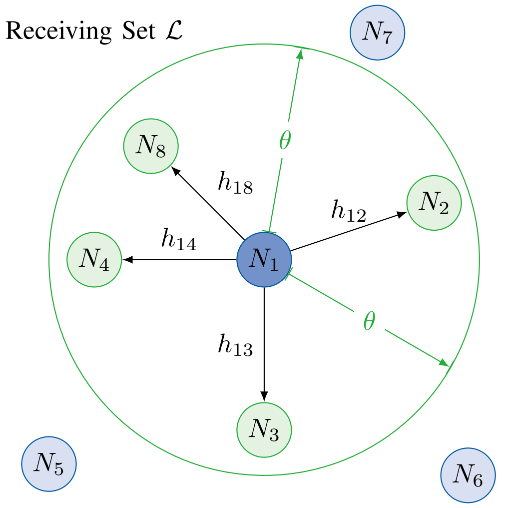


Figure 3: Global receiving set $\mathcal{L}$ in the centralized power control and beamforming scheme in the case of transmitter N_1.

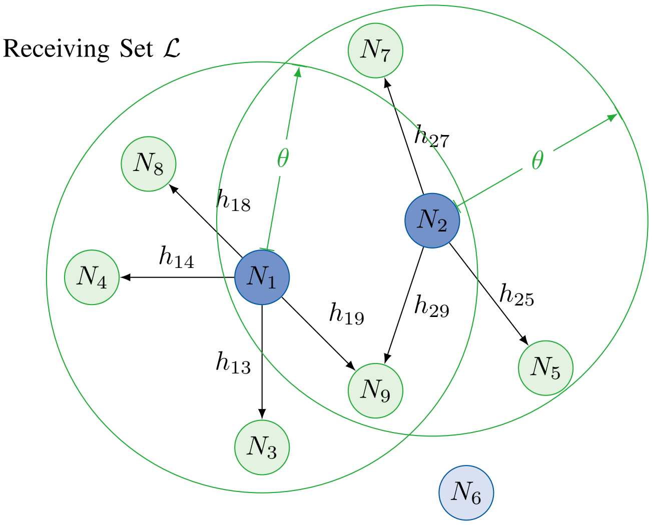


Figure 4: Global receiving set $\mathcal{L}$ in the centralized power control and beamforming scheme in the case of transmitters N_1 & N_2.

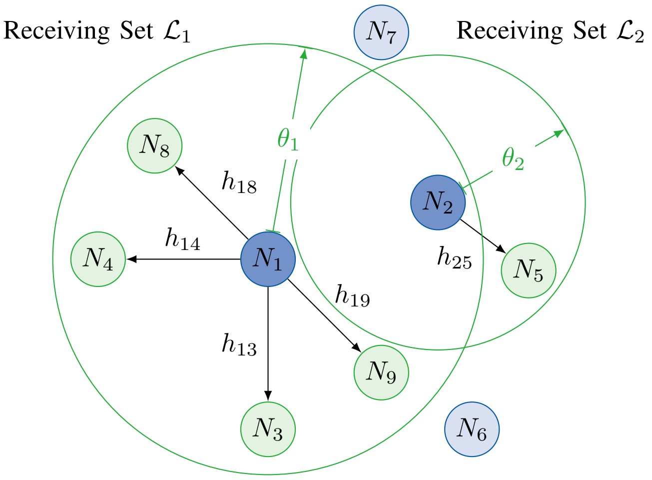


Figure 5: Local receiving sets $\mathcal{L}_1$ & $\mathcal{L}_2$ in the distributed power control scheme in the case of transmitters N_1 & N_2.

B. Distributed Power Control

Operation. We introduce now a distributed approach to transmit power allocation in Glossy. We assume that each node in the network has only local CSI and topography information. This allows each transmitting node m to make independent transmit power decisions, based on the available information. A minimum communication range θ_{min} is specified, but each transmitting node m is allowed to increase the value of θ_m in order to include at least one receiving node in its own local receiving set $\mathcal{L}_m$ as seen in Figure 5 where $\theta_1 \neq \theta_2$.

Analysis. Aiming at minimizing the transmit power of all transmitters while still satisfying the rate constraints in (4), we formulate the optimization problem

$$\begin{aligned} \text{minimize} \quad & W_m \\ \text{subject to} \quad & h_{ml}^* W_m h_{ml} \geq z; \forall l \in \mathcal{L} \\ & W \geq 0 \end{aligned} \tag{9}$$

which can be solved independently for each transmitter m using the closed form solution

$$W_m = \frac{z}{\min_{l \in \mathcal{L}} |h_{ml}|^2} \tag{10}$$

Intuitively explained, each transmitter m adapts its own transmit power to accommodate the receiver l with the worst channel h_{ml}. Therefore, satisfying the rate constraint in (4) for all receivers in his own local receiver set $\mathcal{L}_m$.

V. SIMULATION RESULTS

This section uses simplified system level simulations to evaluate and compare the performance of different power control and beam-forming schemes when applied to state-of-the-art Glossy in terms of energy efficiency. Before discussing our results, we describe the settings and metrics we use.

A. Settings and Metrics

We generate network topologies using a binomial point process with λ nodes randomly and independently placed in a square of side length β. Our results are averaged over 1000 independent realizations for the same λ and β. Irrespective of the network topology, all nodes transmit with rate $R = 250$ kbps which corresponds to the default setting as prescribed by the IEEE 802.15.4 standard.

Our channel gains h_i are modeled as stationary independent according to $h_i = w_i g_i$, where small-scale fading w_i follows a complex normal distribution $\mathcal{CN}(0, 1)$, and large-scale fading g_i depends on the distance d between transmitter and receiver [3, E 5.3]

$$g_i = \begin{cases} 40.2 + 20\log(d) & , d \leq 8\,\text{m} \\ 58.5 + 33\log(d/8) & , d > 8\,\text{m} \end{cases} \tag{11}$$

This corresponds to a path loss exponent of 2 for the first 8 m and a path loss exponent of 3.3 for distances larger than 8 m. To ensure $g_i > 0$ according to (11), we consider only topologies where the distance between any pair of nodes exceeds 0.1 m, which is reasonable in real deployments [25].

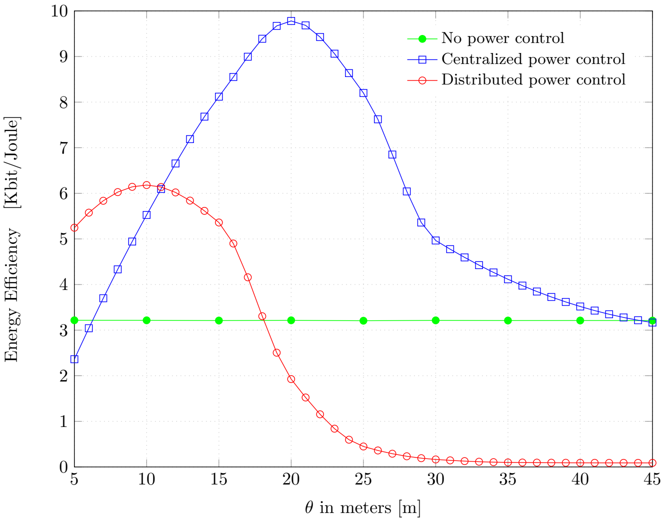


Figure 6: Energy efficiency of standard glossy, centralized and distributed power control and beam-forming schemes for different θ values, in a network that consists of 50 nodes and is 50 m × 50 m in size.

We compare standard Glossy to both a centralized and distributed power control schemes in terms of *energy efficiency*, which is defined as the average amount of data successfully disseminated through the network during one Glossy flood, divided by the energy consumed by the entire network in the process. We compute energy efficiency in Kbit/Joule of the network for packets that carry an 8-byte payload. It is important to note that although the power optimization is done under QoS constraints, this guarantees QoS of individual stages within one flood but not the QoS of an entire flood. Therefore, some nodes may not be able to receive the data due to topography limitations, for example.

We set the re-transmission limit of Glossy to $N = 3$ based on experience from extensive real-world experiments [6], [9]. on the other hand, we set $N = 1$ for our proposed power allocation and beam-forming schemes since the reception of data is insured by our power optimization for single transmissions.

B. Results

To assess the gains in terms of energy efficiency of introducing power control and beam-forming, we first plot in Figure 6 the energy efficiency of Glossy without power control, Glossy with centralized power control and beam-forming, and Glossy with distributed power control and beam-forming. We consider a network of 50 nodes placed in a 50 m × 50 m area for different values of the communication range threshold θ.

Looking at the centralized scheme, we see that the optimum value for θ is around 20 meters achieving almost 10 Kbit/Joule, which corresponds to a three-fold increase in energy efficiency over state-of-the-art Glossy. This, in a sense, serves as an upper bound on the energy efficiency of Glossy when using power control and beam-forming. It can also be seen that the centralized approach performs worst for small values of θ. This is a consequence of having an unconnected graph due to the small range of receiving sets θ, resulting in very low packet reception ratios, hence low energy efficiency.

For the distributed scheme, we observe a gains in energy efficiency over state-of-the-art Glossy up to $\theta = 15$ m. Since each node chooses its own θ dynamically depending on the network topology information, the distributed scheme does not experience graph non-connectivity. Therefore, it outperforms all other schemes for lower values of θ. However, for higher values of θ, each node has a large receiving set $\mathcal{L}_m$ and must satisfy the rate conditions for all $l \in \mathcal{L}_m$ together with stronger overlap between receiving sets $\mathcal{L}_m$. This results in excess transmit power usage, which in turn lowers the energy efficiency significantly.

C. Discussion

There are many ways to formulate a distributed power control and beam-forming strategy. By exploring different approaches to applying power control and beam-forming in Glossy in a distributed, or *semi-distributed* fashion, we can achieve eventually higher energy efficiency gains while approaching the upper bound. In [26] the best response team power control problem for interference channel with local CSI is studied. An algorithm converging to a best response power control policy is introduced and optimum power control policies can be computed. Applying team decision strategies to our power control and beam-forming problem in network flooding is an interesting direction and represents the logical next step following this work.

VI. CONCLUSIONS

In this paper, we study the Glossy protocol with clean-slate physical and medium access control layer. It is shown that flexible power control and distributed multicast beam-forming approaches, well known from coordinated multi-point transmission and reception in cellular communications and standardized in LTE/A, can lead to significant gains in terms of energy efficiency. By studying centralized power assignment, an upper bound on the energy efficiency is acquired which exceeds the energy efficiency of standard Glossy by several folds. We prove that optimal operating setting is dependent on the radius of the receiving set θ; and that for small values of θ, energy efficiency is degraded. Distributed power control and beam-forming is shown to be most advantageous for smaller values of θ, due to the dynamically chosen values of θ independently by each transmitter based on topography information. This suggests to take a new look at the corresponding PHY and MAC standards to make the system ready to address the scalability and efficiency challenges in 5G and beyond.

Acknowledgments. This work was supported by the German Research Foundation (DFG) within the Cluster of Excellence "Center for Advancing Electronics Dresden (cfaed)" and through Priority Programs 1914, and by the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie project 641985 (ETN-5Gwireless).

REFERENCES

[1] M. Simsek, A. Aijaz, M. Dohler, J. Sachs, and G. Fettweis, "5G-enabled tactile internet," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 3, pp. 460–473, March 2016.

[2] J. Åkerberg, M. Gidlund, and M. Björkman, "Future research challenges in wireless sensor and actuator networks targeting industrial automation," in *Proc. of the IEEE INDIN*, 2011.

[3] "IEEE standard for information technology– local and metropolitan area networks– specific requirements– part 15.4: Wireless l (MAC) and (PHY) specifications for low rate (WPANs)," *IEEE Std 802.15.4-2006*.

[4] J. Beutel, B. Buchli, F. Ferrari, M. Keller, and M. Zimmerling, "X-SENSE: Sensing in extreme environments," in *Proc. of DATE*, 2011.

[5] M. Ceriotti *et al.*, "Is there light at the ends of the tunnel? Wireless sensor networks for adaptive lighting in road tunnels," in *ACM/IEEE IPSN*, 2011.

[6] F. Ferrari, M. Zimmerling, L. Thiele, and O. Saukh, "Efficient network flooding and time synchronization with Glossy," in *Proc. of the ACM/IEEE IPSN*, 2011.

[7] O. Landsiedel, F. Ferrari, and M. Zimmerling, "Chaos: Versatile and efficient all-to-all data sharing and in-network processing at scale," in *Proceedings of the 11th ACM SenSys*, NY, USA, 2013, pp. 1:1–1:14.

[8] W. Du, J. C. Liando, H. Zhang, and M. Li, "When pipelines meet fountain: Fast data dissemination in wireless sensor networks," in *Proc. of ACM SenSys*, 2015.

[9] F. Ferrari, M. Zimmerling, L. Mottola, and L. Thiele, "Low-power wireless bus," in *Proc. of the 10th ACM SenSys*, 2012.

[10] M. Zimmerling, L. Mottola, P. Kumar, F. Ferrari, and L. Thiele, "Adaptive real-time communication for wireless cyber-physical systems," *ACM Trans. on Cyber-Physical Systems*, 2016, To appear.

[11] N. D. Sidiropoulos, T. N. Davidson, and Z.-Q. Luo, "Transmit beamforming for physical-layer multicasting," *IEEE Transactions on Signal Processing*, vol. 54, no. 6, pp. 2239–2251, June 2006.

[12] A. B. Gershman, N. D. Sidiropoulos, S. Shahbazpanahi, M. Bengtsson, and B. Ottersten, "Convex optimization-based beamforming," *IEEE Signal Processing Magazine*, vol. 27, no. 3, pp. 62–75, May 2010.

[13] J. Zander, "Performance of optimum transmitter power control in cellular radio systems," *IEEE Transactions on Vehicular Technology*, vol. 41, no. 1, pp. 57–62, Feb 1992.

[14] S. Stanczak, M. Wiczanowski, and H. Boche, *Fundamentals of Resource Allocation in Wireless Networks: Theory and Algorithms*, 2nd ed. Springer Publishing Company, Incorporated, 2009.

[15] S. Schwarz and M. Rupp, "Transmit optimization for the miso multicast interference channel," *IEEE Transactions on Communications*, vol. 63, no. 12, pp. 4936–4949, Dec 2015.

[16] Z. q. Luo, W. k. Ma, A. M. c. So, Y. Ye, and S. Zhang, "Semidefinite relaxation of quadratic optimization problems," *IEEE Signal Processing Magazine*, vol. 27, no. 3, pp. 20–34, May 2010.

[17] R. Mudumbai, D. R. B. Iii, U. Madhow, and H. V. Poor, "Distributed transmit beamforming: challenges and recent progress," *IEEE Communications Magazine*, vol. 47, no. 2, pp. 102–110, February 2009.

[18] R. F. Schaefer and H. Boche, "Physical layer service integration in wireless networks : Signal processing challenges," *IEEE Signal Processing Magazine*, vol. 31, no. 3, pp. 147–156, May 2014.

[19] K. Leentvaar and J. Flint, "The capture effect in FM receivers," *IEEE Trans. Commun.*, vol. 24, no. 5, 1976.

[20] A. Gamal and Y. Kim, *Network Information Theory*. Cambridge University Press, 2011.

[21] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. New York, NY, USA: Cambridge University Press, 2005.

[22] P. Marsch and G. P. Fettweis, *Coordinated Multi-Point in Mobile Communications: From Theory to Practice*, 1st ed. New York, NY, USA: Cambridge University Press, 2011.

[23] M. Grant and S. Boyd, "CVX: Matlab software for disciplined convex programming, version 2.1," http://cvxr.com/cvx, Mar. 2014.

[24] ——, "Graph implementations for nonsmooth convex programs," in *Recent Advances in Learning and Control*, ser. Lecture Notes in Control and Information Sciences, V. Blondel, S. Boyd, and H. Kimura, Eds. Springer-Verlag Limited, 2008, pp. 95–110, http://stanford.edu/~boyd/graph_dcp.html.

[25] M. Ceriotti *et al.*, "Monitoring heritage buildings with wireless sensor networks: The Torre Aquila deployment," in *ACM/IEEE IPSN*, 2009.

[26] P. de Kerret, S. Lasaulce, D. Gesbert, and U. Salim, "Best-response team power control for the interference channel with local CSI," in *ICC 2015, IEEE*, 06 2015.