On packet transmission scheduling for min-max delay and energy consumption in wireless mesh sensor networks

Antonio Capone [a,1] Michał Pióro [b,c,2] Yuan Li [b,3] Di Yuan [d,e,4]

[a] *Information and Communication Technology Department, Technical University of Milan, Italy*

[b] *Department of Electrical and Information Technology, Lund University, Sweden*

[c] *Institute of Telecommunications, Warsaw University of Technology, Poland*

[d] *Department of Science and Technology, Linköping University, Sweden*

[e] *Institute for Systems Research, University of Maryland, USA*

Abstract

Optimization of channel utilization in wireless networks is typically based on transmission parallelization under signal-to-interference and noise constraint assuming minimum frame-length scheduling. In application scenarios like sensor networks this approach may not be suitable since it does not explicitly consider end-to-end packet delay nor energy consumption. In the paper we propose a mixed-integer programming formulation for scheduling optimization in wireless sensor networks characterized by periodic data gathering where minimization of the maximum packet delay and sensor node energy consumption are the main objectives. The model, which assumes cooperation in packet forwarding and interference cancellation, is compared to traditional single path forwarding.

Keywords: wireless scheduling, cooperative forwarding, interference cancellation, delay minimization, energy efficiency, integer programming

[1] Email: `capone@elet.polimi.it`
[2] Email: `michal.pioro@eit.lth.se`
[3] Email: `yuan.li@eit.lth.se`
[4] Email: `di.yuan@liu.se`

1 Introduction

In wireless mesh networks efficient utilization of the radio channel is achieved through parallel transmissions satisfying the signal to interference and noise ratio (SINR) requirement at the receivers. In the common case of *single path forwarding*, the level of cooperation between the nodes is limited when packets are transmitted along their (multi-hop) path. Cooperation of nodes can be achieved by taking advantage of the broadcast nature of radio transmissions, as a packet sent from a node can be received by other nodes. These nodes can then perform *cooperative forwarding* by sending the packet simultaneously to other nodes making the useful signal at a receiving node the sum of the signals transmitting the packet in question. Cooperation can be further extended using *cooperative interference cancellation*. When a receiving node is aware of the scheduled packets to be transmitted by each node in each time slot, it can cancel the interference caused by transmissions of the packets the node has already received [6]. These two mechanisms make meeting the SINR requirement easier, allowing for larger transmission ranges and more parallel transmissions.

The problem of parallel transmission scheduling for single path forwarding has been widely studied [1,5]. Most of the work has been focused on minimum frame-length scheduling that assures the least number of time-slots per frame required for link transmissions by traffic demands [2,9,8]. In multi-hop wireless networks the number of packets to be transmitted per link depends on routing which therefore should also be optimized as to increase network efficiency [3]. For the delay maximization with single path forwarding this paper extends the ideas of [7]. The model for cooperative forwarding with interference cancellation formulated in (2) is original, with some influence of [4].

Minimum frame-length scheduling, however, is not well suited for the investigations of this paper. Our scheduling problem is related to sensor networks that periodically deliver information to the gateways so that all packets for a given session must be sent within the cycle duration. Our basic objective is to schedule the packet transmissions so that the time when the last packet reaches one of the gateways is minimized. At the same time we combine delay minimization with that of minimization of the maximum energy consumed over all the sensor nodes. In the paper we compare the cooperative transmission with interference cancellation scheme with the single path forwarding scheme, using appropriate mixed-integer programming (MIP) formulations. The numerical results show the gains from the former scheme, and illustrate the trade-off between min-max delay and min-max energy consumption.

The centralized scheduling schemes assumed in this paper can be applied in those wireless sensor networks where traffic is almost periodic according to data gathering rounds and a global synchronization is assumed. A global transmission schedule can be centrally computed and then notified to the nodes by a network configuration platform. This kind of scenario reflects realistic applications of monitoring systems in different domains from environmental monitoring to industrial metering. In other scenarios, the performance of a global schedule can be an useful benchmark for distributed protocols.

2 Optimization models

Consider a set of sensor nodes (sensors in short) $\mathcal{N}$ and a set of gateways $\mathcal{G}$. The two sets are disjoint and their sum is denoted by $\mathcal{V}$. Each sensor can originate and retransmit packets destined to gateways while the gateways only receive packets. The network works in cycles. Transmissions and receptions of packets at the nodes within each cycle are scheduled according to TDMA. Each cycle is composed of T subsequent time slots, $\mathcal{T} = \{1, 2, \dots, T\}$. Packets are assumed to be of fixed length—the length of a time slot is the time required to transmit one packet over a link. The set of packets $\mathcal{S}$ to be delivered to the gateways during each cycle is the same for all cycles (a packet may have different contents in different cycles). The sensor that originates packet $s \in \mathcal{S}$ is denoted by o_s ($o_s \in \mathcal{N}$). At the beginning of a given cycle the nodes are awaken and the sensors start sending packets. The packets are being sent and received in the consecutive time slots until every packet reaches one of the gateways. When the last packet is delivered, in slot number $t^*, t^* \leq T$, say, the nodes switch to the sleeping mode until the next cycle begins, so that slots $t^* + 1, t^* + 2, \dots, T$ are unused. In each slot a node can either be in the transmission mode or in the receiving mode or do nothing.

With cooperative transmission, several nodes can simultaneously send or receive the same packet, and nodes are capable of cancelling the signals delivering a packet provided the packet has already been received. Let binary quantity $X_{is}^t, i \in \mathcal{N}, s \in \mathcal{S}, t \in \mathcal{T}$, be equal to 1 if sensor i is sending packet s in time slot t. Besides, let y_{ks}^t be equal to 1 if node $k \in \mathcal{V}$ is has already received packet s by time slot t. Then the SINR condition for node $j \in \mathcal{V}$ to successfully receive packet s in slot t is as follows:

$$\frac{\sum_{i \in \mathcal{N} \setminus \{j\}} p_{ij} X_{is}^t}{\eta + \sum_{k \in \mathcal{N} \setminus \{j\}} p_{kj} \sum_{r \in \mathcal{S} \setminus \{s\}} X_{kr}^t (1 - y_{jr}^t)} \geq \gamma. \tag{1}$$

Above, $p_{ij} = P_i \cdot g_{ij}$ is the power of the signal received at node $j \in \mathcal{V}$ from node i when the latter is in the transmission mode (where P_i is the transmission power of node $i \in \mathcal{N}$, and g_{ij} is the gain of link (i, j)). Besides, η is the noise observed in the nodes, and γ is a given threshold. Note that the power of all the signals carrying packet s received at node j are summed up (in the nominator) while the signals carrying packets different than s and present at node j are cancelled (in the denominator). Certainly, the scheduling must be preplanned for each slot so that interferences are avoided.

The binary formulation of the delay minimization scheduling problem with cooperative forwarding and interference cancellation (CFIC) is given in (2). The formulation uses the following binary variables: X_{is}^t ($X_{is}^t = 1$ if node $i \in \mathcal{N}$ is sending packet $s \in \mathcal{S}$ in slot $t \in \mathcal{T}$); Y_{is}^t ($Y_{is}^t = 1$ node $i \in \mathcal{V}$ is receiving packet $s \in \mathcal{S}$ in slot $t \in \mathcal{T}$); y_{is}^t ($y_{is}^t = 1$ if packet $s \in \mathcal{S}$ is present at node $i \in \mathcal{V}$ by slot $t \in \mathcal{T}$); z_{kjr}^t (auxiliary variable, $z_{kjr}^t = 1$ if node $k \in \mathcal{N}$ is sending packet $r \in \mathcal{S}$ in slot $t \in \mathcal{T}$ and this packet is already present in node $j \in \mathcal{V}$); λ^t ($\lambda^t = 1$ if slot $t \in \mathcal{T}$ allows transmissions).

$$\textbf{CFIC:} \text{ minimize } \; F(\lambda) = \textstyle\sum_{t\in\mathcal{T}} \lambda^t \tag{2a}$$
$$\lambda^{t+1} \le \lambda^t, \quad t \in \mathcal{T} \setminus \{T\} \tag{2b}$$
$$\textstyle\sum_{s\in\mathcal{S}} (X_{is}^t + Y_{is}^t) \le \lambda^t, \quad i \in \mathcal{V}, t \in \mathcal{T} \tag{2c}$$
$$\textstyle\sum_{t\in\mathcal{T}} Y_{is}^t \le 1, \quad i \in \mathcal{V}, s \in \mathcal{S} \tag{2d}$$
$$y_{is}^t \le \textstyle\sum_{\tau\in[1,t]} Y_{is}^\tau, \quad s \in \mathcal{S}, i \in \mathcal{V} \setminus \{o_s\}, t \in \mathcal{T} \tag{2e}$$
$$y_{o_s s}^1 = 1, \; \textstyle\sum_{g\in\mathcal{G}} y_{gs}^T \ge 1, \quad s \in \mathcal{S} \tag{2f}$$
$$X_{is}^t \le y_{is}^t, \quad i \in \mathcal{N}, s \in \mathcal{S}, t \in \mathcal{T} \tag{2g}$$
$$X_{gs}^t = 0, \quad g \in \mathcal{G}, s \in \mathcal{S}, t \in \mathcal{T} \tag{2h}$$
$$\begin{aligned}&\tfrac{1}{\gamma} \textstyle\sum_{i\in\mathcal{V}\setminus\{j\}} p_{ij} X_{is}^t + \tfrac{1}{\gamma} M(j)(1 - Y_{js}^t) \ge \\ &\eta + \textstyle\sum_{k\in\mathcal{N}\setminus\{j\}} \sum_{r\in\mathcal{S}\setminus\{s\}} p_{kj} z_{kjr}^t, \quad j \in \mathcal{V}, s \in \mathcal{S}, t \in \mathcal{T}\end{aligned} \tag{2i}$$
$$\begin{aligned}&z_{kjr}^t \le X_{kr}^t, \; z_{kjr}^t \le 1 - y_{jr}^t, \; z_{kjr}^t \ge X_{kr}^t - y_{jr}^t, \; z_{kjr}^t \ge 0, \\ &\qquad j \in \mathcal{V}, k \in \mathcal{N} \setminus \{j\}, r \in \mathcal{S}, t \in \mathcal{T}\end{aligned} \tag{2j}$$
$$\text{all variables binary.} \tag{2k}$$

In the formulation, objective (2a) minimizes the total number of slots required to transmit all packets from their origins to the gateways, i.e., the delay. Constraint (2b) forces all time slots after the first unused one to be also unused. The next two constraints ensure that in any slot a node can either transmit or receive or do nothing (inequality (2c)) and that a node receives a given packet at most once (inequality (2d)). Constraints (2e) and (2f) define the variables y and set their boundary conditions, respectively. Constraint (2g) does not allow a packet to be transmitted by a sensor node before it is received while constraint (2h) does not allow the gateways to transmit at all. The SINR constraint previously defined in (1) is formulated in a linear form by (2i) together with constraints (2j) that define the auxiliary variables z in a proper way. Note that the auxiliary variables z ($z_{kjr}^t = X_{kr}^t \cdot y_{jr}^t$) can be assumed continuous, as for binary X and y, constraints (2j) force them to be binary. Note that the "big M" values $M(j)$ in (2i) (used for cancelling the SINR constraint when node j is not receiving packet s in time slot t) can be set to $M(j) = \gamma(\eta + \sum_{k\in\mathcal{N}\setminus\{j\}} p_{kj})$, assuming the worst case when all nodes besides j are transmitting packets that have not been received by node j yet.

In the sequel, formulation (2) will be called CFIC(a). A modification of

(2) that minimizes the maximal energy consumption E, i.e.,

$$\text{minimize } E \quad \text{subject to} \quad E \geq \sum_{t\in\mathcal{T}} \sum_{s\in\mathcal{S}} (\beta X_{is}^t + \omega Y_{is}^t),\ i \in \mathcal{N} \tag{3}$$

and (2b)-(2k), will be referred to as CFIC(b). Coefficients β and ω ($\omega \leq \beta$) correspond to the energy required by a node to send a packet and to receive a packet, respectively. Note that the assumption we have made above is that the energy consumption of an active node has two components, one for the baseband processing and one for the radio transmission. As observed in most of hardware platforms, the energy consumption for baseband is almost constant regardless of the computation load. A node is active only in time slots when it has to either transmit or receive. In reception slots only the baseband component is considered, while in transmission slots only the radio component is summed up.

In the next section we will compare the CFIC scheme with the standard single path forwarding (SPF) scheme. In SPF only unicast transmissions are allowed, meaning that when a node transmits, the transmitted packet is destined only for one particular node so that other nodes do not receive that packet. In effect, in SPF cooperation forwarding and interference cancellation are not applied. Thus, transmissions correspond to links and for a link (i, j) from node i to j the SINR condition enabling successful transmission of a packet in slot $t \in \mathcal{T}$ is as follows:

$$\frac{p_{ij}}{\eta + \sum_{k\in\mathcal{N}\setminus\{i,j\}} p_{kj} X_k^t} \geq \gamma, \tag{4}$$

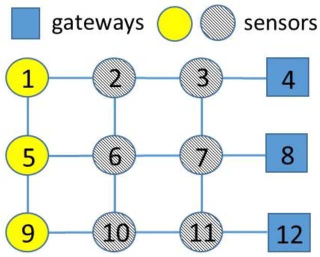
where $X_k^t, k \in \mathcal{N}, t \in \mathcal{T}$, is a binary quantity equal to 1 when node k is transmitting a packet in slot t. It is assumed that a link (i, j) is provided if, and only if, $\frac{p_{ij}}{\eta} \geq \gamma$.

For the space reason, the SPF binary problem formulations we have used in the computations presented in Section 3 for delay minimization (called SPF(a) in the sequel) and for energy saving (called SPF(b)) are omitted here. SPF(a) is an improved version of model (6) presented in [7] (where energy saving was not considered).

3 Numerical study

Below we compare the performance of the CFIC and SPF schemes in terms of min-max packet delay (CFIC(a) vs. SPF(a)) and of min-max energy consumption (CFIC(b) vs. SPF(b)). In the examples we assume $g_{ij} = d_{ij}^{-4}$ (where d_{ij} is the node distance), $P_i = 0.1$ W for all nodes, and $\eta = 10^{-13}$ W.

In comparison to SPF, both cooperative forwarding and interference cancellation take advantage of the possibility that a packet could be present at multiple nodes, due to the broadcast nature of wireless transmissions. In con-

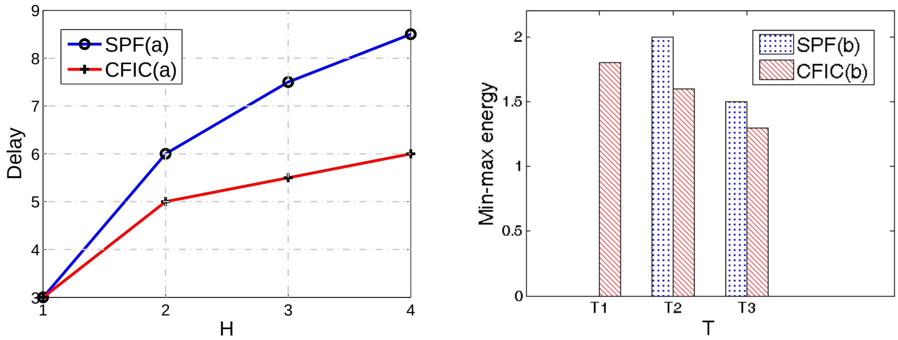


	s	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9
SPF(a)	1	1->2				2->3		3->4		
	2				5->6		6->7			7->8
	3		9->10	10->11					11->12	
CFIC(a)	1			1->2	1,2 ->3		2,3->4			
	2	5-> 6,1	1,6 ->2,7	6,7 ->3,10	6,7 ->11	3,7 ->8				
	3		9->5		5,9 ->10	10 ->11	5,10,11 ->12			

Fig. 1. An illustrative example comparing the two models

sequence, the two schemes aim at improving the numerator and the denominator of the SINR constraint, respectively. This makes them complementary and justifies investigating their joint effect as in CFIC. To illustrate the difference between the two schemes, consider the example shown in Figure 1, where the length of each link is 250 m so that with SPF each node can send packets only along these links, as the assumed SINR threshold $\gamma = 25$ corresponds the maximum transmission distance 251 m. There are three packets with the originating nodes 1,5,9, respectively. In this setting, for SPF only one transmission per time slot is feasible (because of interference). Therefore in the (optimal delay) solution for SPF(a), each packet follows its shortest path to the nearest gateway and hence the minimum delay (the same for all three packets) is equal to 9 slots. This solution is illustrated in the upper right part of Figure 1, where each entry (corresponding to a given packet and a given slot) indicates the transmitting link. With CFIC, however, broadcasting of packets and interference cancellation are admitted, and this leads to a much better CFIC(a) optimal solution with the delay equal to 6 slots, depicted in the lower right part of Figure 1. Each entry shows the set of nodes (on the left of the arrow) that simultaneously send the corresponding packet in the corresponding slot, and the set of nodes (on the right of the arrow) that receive this packet. Note that in slot $t = 1$ packet $s = 2$ is sent from node 5 to nodes 1 and 6. In slot $t = 2$, nodes 1 and 6 send packet $s = 2$ and this packet is received in nodes 2 and 7. Simultaneously, packet $s = 3$ is sent from node 9 to node 5—this is possible because node 5 already stores packet 2 so the transmission from nodes $1, 6$ are cancelled at 5. In $t = 3$, due to cooperative transmission of nodes $6, 7$, node 3 can receive packet 2 even though node 1 is active (in $t = 3$ node 1 is sending a packet $s = 1$ to node 2).

Considering the min-max energy consumption, suppose $\beta = \omega = 0.5$ (the values used also in the subsequent examples). We observe that the SPF(a) solution with min-max energy consumption equal to 1 is also optimal for SPF(b). It happens that for the considered network the optimal solution of CFIC(b) (assuming $T = 9$) is the same as the solution of SPF(b) (SPF solutions are feasible for CFIC), and thus of SPF(a). Note that the min-max energy of the CFIC(a) solution $E = 2$ is twice as large.



(a) Delay versus hops (b) Energy versus T

Fig. 2. Comparisons of CFIC and SPF

Now we examine networks with 15 nodes (out of which, one node is a gateway and the rest are the sensors), placed randomly in a square of 1 by 1 km. The SINR threshold γ is equal to 15. For each such topology, we consider four cases for $H = 1, 2, 3, 4$. Each case results from randomly selecting a subset of three sensors among those nodes in $\mathcal{N}$ that are distant from the gateway by exactly H hops (i.e., the shortest path to the gateway contains H links). These three sensors are assumed to send one packet each (in each cycle), and the rest of the sensors are used only for transiting packets. Min-max delay versus H is shown in Figure 2a (each result is averaged over 10 independently generated network topologies). As could be expected, the delay as well as the difference in delay between the two schemes increases as H increases.

Min-max energy E for the two schemes vs. three cycle lengths $T1$ (minimum delay of CFIC(a)), $T2$ (minimum delay of SPF(a)) and $T3$ (the upper bound) is shown in Figure 2b. We again consider random networks with 15 nodes, but now for each tested network we randomly select one gateway and three sensors. If the two schemes happen to have the same min-max delay for a generated instance, we discard it and re-generate until a different min-max delay is exhibited. The results are averaged over 10 networks. No result is reported for SPF(b) for $T = T1$ since then SPF is infeasible (CFIC is feasible in this case thanks to cooperative transmission and interference cancellation). Certainly, since any feasible solution of SPF is feasible for CFIC, the latter model is never worse that the former in terms of energy consumption. Besides, it is observed that with increasing T, the difference in min-max energy consumption between the models decreases.

4 Concluding remarks

In the paper we have studied an optimization model for cooperative forwarding with interference cancellation (CFIC) in wireless sensor meshed networks.

Using it, we have compared efficiency of CFIC with the standard single path forwarding (SPF). It turns out that in terms of delay the sophisticated cooperative CFIC scheme can perform much better that the SPF, but this is achieved on the expense of larger energy consumption. When the energy objective alone is considered, using CFIC is not that helpful.

The numerical results are reported for networks with a limited number of nodes. This is because the presented MIP model is hard to solve and needs enhancements (such enhancements are currently under investigation). We expect that for sensor networks with a larger number of nodes and sources the efficiency superiority of CFIC over SPF will become more profound.

Acknowledgement: The paper is a result of cooperation within the People Programme (Marie Curie Actions) of the EU Seventh Framework Programme FP7/2007-2013/ under the REA grant agreement no. 324515 (MESH-WISE).

References

[1] M. Andrews and M. Dinitz. Maximizing Capacity in Arbitrary Wireless Networks in the SINR Model: Complexity and Game Theory. In *IEEE INFOCOM*, pages 1332–1340, April 2009.

[2] P. Bjorklund, P. Varbrand, and D. Yuan. Resource Optimization of Spatial TDMA in Ad hoc Radio Networks: a Column Generation Approach. In *IEEE INFOCOM*, pages 818–824, March 2003.

[3] A. Capone, G. Carello, I. Filippini, S. Gualandi, and F. Malucelli. Routing, Scheduling and Channel Assignment in Wireless Mesh Networks: Optimization Models and Algorithms. *Ad Hoc Networks*, 8(6):545–563, 2010.

[4] A. Capone, S. Gualandi, and D. Yuan. Joint Routing and Scheduling Optimization in Arbitrary Ad Hoc Networks: Comparison of Cooperative and Hop-by-hop Forwarding. *Ad Hoc Networks*, 9(7):1256–1269, 2011.

[5] O. Goussevskaia, R. Wattenhofer, M.M. Halldorsson, and E. Welzl. Capacity of Arbitrary Wireless Networks. In *IEEE INFOCOM*, pages 1872–1880, April 2009.

[6] S. Katti, S. Gollakota, and D. Katabi. Embracing wireless interference: Analog network coding. In *ACM SIGCOMM*, pages 397–408, 2007.

[7] Y. Li, A. Capone, and D. Yuan. On End-to-end Delay Minimization in Wireless Network under Physical Interference Model. In *IEEE INFOCOM (accepted)*, April 2015.

[8] M. Pióro, M. Żotkiewicz, B. Staehle, D. Staehle, and D.Yuan. On Maxmin Fair Flow Optimization in Wireless Mesh Networks. *Ad Hoc Networks*, 13(0):134–152, 2014.

[9] P. Wan, O. Frieder, X. Jia, F. Yao, X. Xu, and S. Tang. Wireless Link Scheduling under Physical Interference Model. In *IEEE INFOCOM*, pages 838–845, April 2011.