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Cross-Layer Optimization of Multipoint Message Broadcast in MANETs

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***Abstract*—Multipoint-to-multipoint message broadcast is a demanding application scenario in ad-hoc networks. Adaptive management of wireless resources is necessary to support such applications in a safety critical context. In this work we study adaptation of transmission rate and power to varying densities of ad-hoc nodes. Our approach is to construct a cross-layer model building on existing models for physical and link layers. To enable optimization in relation to metrics of end-to-end delay and message reception probability a model of flooding broadcast is proposed as a part of the cross-layer model.**

In a simulation study we show that adaptation of transmission power and rate can be necessary to achieve delay requirements and maximize message reception probability. Compared to simulation our cross-layer model based optimization approach generates slightly more conservative parameter settings. It is further shown how correlated losses have a significant impact on the robustness of the broadcast technique.

I. Introduction

Adaptive management of wireless resources in ad-hoc scenarios is necessary to utilize the shared medium resources optimally under varying conditions caused by mobility and wireless channel properties. One of the more demanding application scenarios is multipoint-to-multipoint (mp-to-mp) broadcast. In a group of nodes, each node has messages to disseminate to all other nodes while receiving messages from all other nodes as well. This is a highly relevant scenario in car-to-car communication, where messages contain information about road conditions and abrupt changes in neighbour car movement (e.g. emergency braking)[1]. The information is used to increase traffic safety and improve traffic flow. Consisting of multiple sources periodically sending and forwarding messages, obviously, such communication scenarios have a potential to cause heavy contention in the wireless medium which may affect safety properties of the applications. To enable such safety critical applications, under varying conditions, we study distributed approaches to link adaptation in mobile nodes in IEEE 802.11 based vehicular networks.

Two significant link adaptation parameters are transmission power (*tx power*) and transmission rate (*tx rate*). In ad-hoc networks, adaptation of such parameters to network conditions is mainly targeted at improving overall throughput and delay while reducing power consumption [2]. In *unicast settings*, tx power control is commonly applied to optimize single hop connections [3][4] as well as in routing and topology control [2][5] to ensure full and reliable network connectivity while reducing collision domains and conserving energy. Power minimization has also been a studied topic in *broadcast settings*. In work of [6][7][8] approaches are made to minimize tx power of the individual nodes while maintaining broadcast coverage at the cost of transmissions in more hops. This approach yields a reduction in the number of nodes in transmission range and thereby a reduction in redundancy. It is however not thoroughly studied what impact the minimum power objective has on reliability when considering unreliable channels and cases where contention is high.

A dominant part of other work in optimization of broadcast performance focuses on efficient network layer broadcasting techniques to reduce number of forwarding transmissions, end-to-end delay and to increase coverage [9][10]. These techniques are typically based on assumptions of fixed transmission range and rate. A relevant option is to further improve the overall performance and reliability of such protocols by also considering adaptation of link and physical layer parameters.

In this work we study the potential of cross-layer optimization (CLO) of the mp-to-mp broadcasting. We consider possibilities of controlling layer parameters of *tx power* and *tx rate*. In contrast to a dominant part of existing work our focus is not to reduce power consumption, which is less critical in vehicular scenarios than in battery-driven sensor network scenarios. Instead our primary aim is to optimize performance and reliability metrics of *end-to-end message delivery delay* (D_{e2e}) and *successful message delivery probability* (P_{smd}) in relation to constraints set by QoS requirements from an application. This requires to analyze the following tradeoffs: I) High tx power increases the collision domain and amount of redundant nodes but may reduce end-to-end delays due to fewer hops to the network edge. II) High tx rate gives less contention (and delay), whereas employing more resilient modulation schemes (lower rates) increases transmission range without increasing the collision domain. Our cross-layer approach is based on an overall cross-layer model including a basic broadcast mechanism and existing models of fast fading channels and MAC.

The paper is organized as follows: Section II describes the model based optimization approach including the main cross-layer model and submodels based on existing work. In section III, the broadcast model is introduced and finally in section IV, optimization results are evaluated in a simulation study.

II. Optimization Approach and System Models

A stretch of highway represents the scenario in which optimal settings for *tx power* and *tx rate* are needed. We consider a static snapshot of the relative distances between cars where the width of the road is considered insignificant and the cars are in a straight line. For succeeding cars, the spacing is assumed to be equal, as depicted in fig. 1.
The applied optimization approach takes its starting point in a *broadcast source* node (So), which broadcasts messages within a limited area (zone) defined by the application. It is assumed that in general the node farthest from So, the edge node, will experience the worst end-to-end delay and has the highest risk of not receiving a message. Thus, the optimization goal is defined to maximise P_{smd} and keep D_{e2e} within requirements for the edge node.

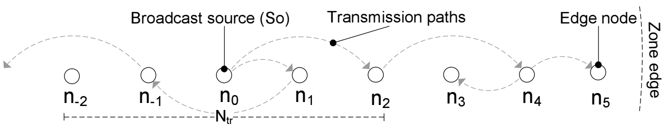

Figure 1. Positions and tx range ($N_{tr}/2$) of broadcasting nodes in highway.

In the following a cross-layer model is presented that allows P_{smd} and D_{e2e} to be evaluated for the edge node, given *tx power*, *tx rate* and node density.

A. Cross-Layer Model

The cross-layer model is built from sub-models covering individual functionalities in a TCP/IP protocol stack on top of IEEE 802.11b link and physical layers. These sub-models are developed as individual modules, to allow extension of selected model parts. The main model is presented in fig. 2. Grey boxes are sub-models representing protocol stack functionalities, where the remainder are equations of output metrics and intermediate variables. In the following we introduce the main parameters and equations of the model. In order to maintain an acceptable computational complexity, the variables and parameters that are passed between submodels and the output variables are scalars. For random variables the mean values are used.

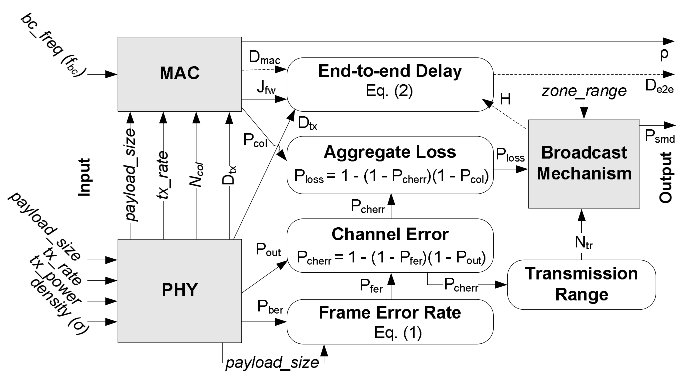

Figure 2. Components of the overall optimization model.

The probability of a frame loss due to channel variations, P_{cherr}, is given in the *Channel Error* equation of fig. 2. P_{out} is the outage probability which describes the probability that the signal power in a receiving node drops below the receive threshold leading to a frame loss. Assuming independent bit errors, the frame error probability for a frame transmitted using the short preamble option for IEEE 802.11b [11] is:

$$P_{\text{fer}} = 1-(1-P_{\text{e}_{\text{DBPSK}}})^{n_{\text{pre}}}\cdot(1-P_{\text{e}_{\text{DQPSK}}})^{n_{\text{hdr}}}\cdot(1-P_{\text{e}_{Mod}})^{n_{\text{frame}}} \quad (1)$$

where P_{ex} is the BER of the used transmission scheme for different parts of the frame transmission and n_X are the number of bits in the preamble, header and MAC frame. Frame losses can also be caused by collisions represented by the collision probability P_{col}. Thus, the overall probability of a loss of a transmission P_{loss} is given from the *Aggregate Loss* equation, assuming independence of P_{col} and P_{cherr}.

The output metric P_{smd} is calculated from the broadcast model which is described in Section III. As input, the model needs P_{loss}, the transmission range N_{tr} and the zone range. Given the node density, the transmission range is defined as the mean amount of nodes reached by a transmission. We define the transmission range as the nodes where the probability of a successful reception in a free channel is ≥ 0.5.

The end-to-end delay D_{e2e} is defined in terms of the number of hops H, and the delays that occur at each hop:

$$D_{\text{e2e}} = J_{\text{fw}}(H-1) + (D_{\text{mac}} + D_{\text{tx}} + D_{\text{q}})H \quad (2)$$

In (2) the forwarding jitter J_{fw} is the mean of a random delay, which is added to the scheduled transmission time in the flooding broadcast scheme to reduce the collision probability when *forwarding* a broadcast (see [9]).

The transmission delay D_{tx} depends on the PHY mode and the frame size and can easily be obtained from [11]. Deriving the MAC delay, D_{mac}, and link layer interface queueing delay D_{q}, however, requires more extensive modelling work to include influences from contention window size and the number of contending nodes. In this work a simple queueing based model approach has been applied to identify channel utilization and saturation points where D_{e2e} increases significantly. This model is described in section II-C. In the following the individual submodels are presented.

B. PHY Model

The PHY model must provide the probabilities for avg. bit error P_{ber} and outage P_{out}. These are depending on the characteristics of the channel model. The wireless channel in the considered stretch of highway is characterized by a rural environment. The channel model considered in this work is based on the two-ray ground reflection model in conjunction with a Ricean [12] fast fading model. In a Ricean channel, P_{ber}, can be derived from the avg. bit error probability for an AWGN channel using eq. (6.50) in [13]. However, due to the computational complexity of P_{ber} for the CCK modulation schemes with tx rates of 5.5 and $11\,$Mbit/s, only the DBPSK and DQPSK with tx rates of 1 and $2\,$Mbit/s, respectively, have been implemented in the optimization model. The expression used to calculate the bit error probability for DBPSK has been derived analytically and is given in terms of the Rice factor K and the SNR $\frac{E_b}{N_0}$ in (3).

$$P_e = \frac{M}{2} exp(K(M-1)), \text{ where } M = \frac{(1+K)}{(1+K)+\frac{E_b}{N_0}} \quad (3)$$

The bit error probability of PQPSK is obtained numerically. For Ricean fading P_{out} is obtained as described in eq. (6.46) [13].

The PHY model also provides N_{col}, which is the mean number of nodes that will obtain an SNR above the busy sensing threshold [11] in a transmission. Notice that $N_{\text{col}} > N_{\text{tr}}$.

C. MAC Model

The MAC submodel mainly provides the collision probability P_{col} and the channel utilization ρ.

a) Collision probability: The calculation of P_{col} is given from equations (8),(11) and (12) in [14], which is based on the assumption that all nodes always have a packet ready for transmission. In the considered multipoint broadcasting application this is not necessarily the case and the outcome of the model may therefore be too pessimistic in these cases. It must be noted that we assume standard IEEE 802.11 MAC behaviour where in the case of layer 2 broadcasts, a fixed size contention window is used.

b) Channel utilization: In order to establish a basic approach for modelling D_{q} we consider a single server queueing system where μ is the mean rate at which a node gains access to the medium, λ is composed of the arrival rate of broadcasts from the application layer and forwards from other nodes, and $\rho = \frac{\lambda}{\mu}$ is the channel utilization. We may obtain $\lambda = f_{\text{bc}}(1 + (N_{\text{zone}} - 1)P_{\text{smd}})$, where f_{bc} is the broadcast frequency, N_{zone} is the number of nodes in the zone, and P_{smd} is the probability that a broadcast is received successfully by a node, which is then able to forward the broadcast. Further, the achievable medium access rate for each node is in the interval $\frac{1}{D_{\text{tx}} \cdot N_{\text{col}}} \leq \mu \leq \frac{2}{D_{\text{tx}} \cdot N_{\text{col}}}$, where D_{tx} is the transmission time of a frame including DIFS, and N_{col} is the number of nodes within busy sensing range. The time used for decrementing the contention window counter is omitted in μ as it is considered negligible compared to D_{tx}. The upper bound of μ results from the case when parallel transmissions (most likely leading to collisions though) occur in the considered one dimensional topology. In the following we will consider a heuristic estimate of $\mu = \frac{3}{2 \cdot D_{\text{tx}} \cdot N_{\text{col}}}$, as it is in the middle of the interval.

III. FLOODING BROADCAST MODEL

The studied network layer broadcast protocol in this work is flooding broadcast where every node forwards each received unique message once. A high level of redundancy makes flooding broadcast robust to losses but also greedy in the use of channel resources. In existing work [9], flooding broadcast is considered a baseline for comparison while its basic principles make it useful in this initial model study. The outcome of the flooding broadcast model is a metric of P_{smd} for each node based on $P_{\text{s}} = (1 - P_{\text{loss}})$ and the mean amount of nodes that can receive a frame transmission. As a basis for the model construction the following assumptions have been made:

(I) **Equal transmission probability:** The probability of a successful error-free reception, P_{s}, is considered to be the same for any node in the network.

(II) **Independent reception probabilities:** P_{s} is assumed to be independent for each node.

(III) **Time invariant P_{s} during BC:** P_{s} is assumed not to vary throughout the duration of a broadcast.

The flooding broadcast model consists of two parts. An *analytical* model for a fully connected network and an *empirical* model to include partially connected networks.

c) Fully connected network model: In a fully connected network (FCN) it is assumed that all nodes receive a transmission successfully with probability P_{s}. To derive P_{smd} the approach is to calculate the probability that all potential paths from a source node So to a sink node Si will *fail*. For a two node network this probability is obviously $P_{\text{f}}(So \rightarrow Si) = 1 - P_{\text{s}}$. When introducing more nodes, other intermediate paths exist between So and Si. $M(i,\ j)$ is the probability that these intermediate paths will fail; i is the amount of nodes that have received a copy of the message and are ready to forward it. j is the amount of neighbour nodes in a set N (*not* including Si) who have not received the message yet. Thus, for a network consisting of three nodes we have:

$$\begin{aligned} 1 - P_{\text{smd}} &= P_{\text{f}}(So \rightarrow Si)M(1,\ 1) \\ where\ M(1,\ 1) &= [(1 - P_{\text{s}}) + P_{\text{s}}(1 - P_{\text{s}})] \end{aligned} \quad (4)$$

Figure 3 depicts two examples of how a transmission can evolve in a network of five nodes. In (α) only node a receives the first transmission. Subsequently, the transmission continues via nodes b and c. $M(1,2)$ is the probability that the transmission from a fails to reach Si directly or via b and c. Notice, So has already sent a copy of the message and does not transmit it further. In (β) two nodes have received the first transmission and $M(2,1)$ expresses the probability that transmissions from a and c directly and via b will fail. In (5) $M(1,3)$ is given from expressions of $M(1,2)$ and $M(2,1)$.

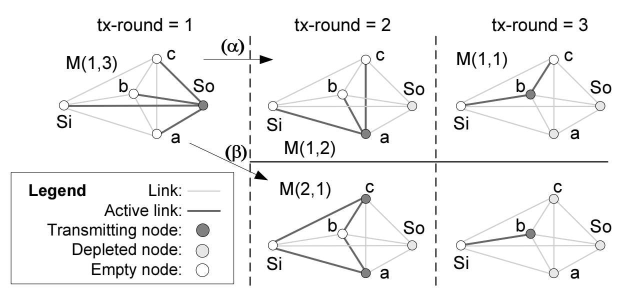

Figure 3. Two examples of broadcast progress in a fully connected network.

$$\begin{aligned} M(1,\ 3) = &\binom{3}{0} P_{\text{s}}^0 (1 - P_{\text{s}})^3 + \binom{3}{1} P_{\text{s}}^1 (1 - P_{\text{s}})^3 M(1,\ 2) \\ &+ \binom{3}{2} P_{\text{s}}^2 (1 - P_{\text{s}})^3 M(2,\ 1) + \binom{3}{3} P_{\text{s}}^3 (1 - P_{\text{s}})^3 \end{aligned} \quad (5)$$

Recognising the recursive elements of (5), an expression for $M(i,j)$ can be defined for any $i,\ j \in N$:

$$M(i,j) = \begin{cases} 1 & \text{for } i = 0,\ j > 0 \\ 1 & \text{for } i > 0,\ j = 0, \quad i,\ j \in N \\ g(i,j) & \text{otherwise} \end{cases}$$

$$g(i,j) = \sum_{q=0}^{j} \binom{j}{q} (1-P_{\mathrm{s}})^q \left[1-(1-P_{\mathrm{s}})^i\right]^q \cdot \left[(1-P_{\mathrm{s}})^i\right]^{j-q} M(q, j-q) \tag{6}$$

Finally from (7) P_{smd} can be calculated for any number of nodes in a FCN that corresponds to the assumptions initially presented in this section.

$$P_{\mathrm{smd}} = 1 - P_{\mathrm{f}}(So \rightarrow Si)M(1,\ j) = 1-(1-P_{\mathrm{s}})M(1,\ j) \quad \text{where } j = \text{number of nodes in } N \tag{7}$$

A simulation of flooding broadcast in an FCN has been implemented in MATLAB in compliance with assumptions I-III. A comparison of the results from simulation to the model verifies that the model accurately provides P_{smd} for varying P_{s} and node size of the FCN.

d) Partially connected network model: The FCN model must be extended to cover more realistic settings of partially connected networks (PCN) where not all nodes are in reach of each other.

The case of PCN is increasingly complex to model in a similar manner as in the fully connected case. First of all the probability P_{smd} has to be established individually for each node. In addition, a broadcast can evolve in many different ways. As an example, fig. 1 depicts a broadcast for a transmission radius of 2 nodes. Essentially, a message may propagate in either direction in relation to the source. As a result a large amount of transmission paths exist between any two nodes. Exact analysis as conducted in the FCN model, thus, becomes intractable.

The alternative option considered for the PCN model is to introduce an empirical approach. The empirical model is partially based on the FCN model and simulation. The message reception conditions in the area around the source node, So, within a radius of $N_{tr}/2$ have a good resemblance to the FCN model. Thus, the FCN model is a useful approximation of P_{smd} to this range of nodes, which is denoted the *So neighbourhood*. To include behaviour outside the So neighbourhood a MATLAB based simulation model of the broadcast mechanism has been implemented. The simulation evaluates transmissions in rounds similar to fig. 3 to obtain P_{smd} for individual nodes. Since the conditions for the simulation are fairly basic little effort is required to generate results with a high sample count for permutations of transmission range and P_{s}. To represent results from simulation in a compact form the progress of P_{smd} outside the Si neighbourhood has been fitted to a polynomial function of third degree, $P_{\mathrm{smd}} = f(x), x = [1, \ldots, N]$ where N is the zone edge node. As a result only four parameters need to be stored for each permutation of R and P_{s} making it suitable for implementation with limited requirements for storage.

The PCN model has been implemented in an ns-2 environment with the *simple MAC* component adapted to include loss behaviour corresponding to the assumptions I-III (controllable P_{s}). The comparison between simulation and model is depicted in fig. 4, which shows a very good correlation between the model and simulation results. The empirical model is generated with a step size in P_{s} of 0.01. The model has been created from an assumption that the stretch of nodes is infinitely long. In a realistic setting a node close to the edge of a network will have fewer forwarding neighbours resulting in a little lower P_{smd} than the model predicts as seen in fig. 4.

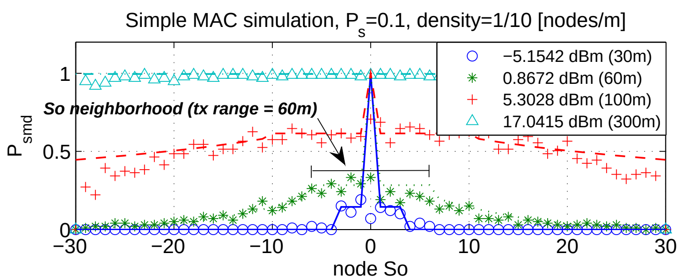

Figure 4. Broadcast model (lines) vs. simple MAC simulation (markers).

The broadcast model assumptions have been revisited from initial results obtained from a detailed ns-2 simulation environment, as described in section IV. It has been seen that (I) seems to be a reasonable assumption for most nodes. Also, as density and transmission requirements of nodes do not change significantly during a broadcast, assumption (III) also seems valid. In many cases P_{loss} is influenced by collisions meaning that many losses, in contrast to assumption (II), are correlated. This impact of this is analysed and discussed further in the following section.

IV. Results and Discussion

This section presents a comparison of output from the cross-layer model and reference data based on simulation runs from a detailed ns-2 simulation setup. Extensions [15] have been added to ns-2 v. 2.29 for correct IEEE 802.11 MAC behaviour and bit-error probabilities in a Ricean channel. A scenario is studied where nodes are placed in equidistant locations as shown in fig. 1 at a stretch of $1000\,m$. Broadcasts are evaluated from an So node at $\sim 500\,m$ to the two edge nodes within a zone range of $300\,m$. The broadcast message size is $30\,bytes$ and application requirements are $D_{\mathrm{e2e}} = 160\,ms$ and $P_{\mathrm{smd}} = 99\,\%$. Further details of the simulation environment can be found in [16].

Model and simulation results are compared for different configurations in terms of *density* (σ) and *broadcast frequency* (f_{bc}) for different settings of *tx rate* and *tx power*. We will use the notation (*tx rate*, $\frac{1}{\sigma}$, f_{bc}) to for each considered case in which we vary the *tx power*. For simplicity, tx powers are in the following converted to approximated tx ranges using a two-ray PHY model. The simulation is for practical reasons evaluated at a coarse resolution while more evaluation points are used for the model. In the following we initially study the effects of varying *tx power* for a single case, and secondly we evaluate the overall performance of the optimization scheme for a selection of cases.

Fig. 5 (A) depicts a comparison for simulation and model of P_{s} and P_{smd} for varying *tx power* at a fixed density $\sigma = \frac{1}{30}\,\frac{nodes}{m}$. In general P_{s} decreases as *tx power* is increased due to an increasing amount of collisions. The model estimate is a little lower than the simulation. This is likely an effect of the simplifying assumptions used to obtain P_{col}. For increasing *tx power*, P_{smd} also increases as more nodes are reached by a transmission. The increased robustness from more nodes, in the considered case, also means that a nearly constant level of P_{smd} is obtained despite the decrease in P_{s}. For the model P_{smd} converges to 1, whereas, the simulation P_{smd} converges to ~ 0.6. The main cause of this difference is found in assumption (II). That is, in contrast to independent reception probabilities in the model, many losses are correlated due to collisions in reality. As a result there is a significant risk of multiple nodes simultaneously failing to receive a transmission. The convergence point of P_{smd} therefore primarily depends on the probability that the initial broadcast from the So node is not received successfully by any neighbor nodes. This is likely to occur in the presence of correlated collisions. If an So broadcast is received by just a few nodes, the redundancy of flooding practically ensures coverage. This vulnerability of the initial broadcast makes the flooding broadcast scheme less robust than the model suggests. Despite this difference, the model and simulation results have interesting similarities. Tab. I contains ranges of optimal $P_{\text{smd}}^{\text{mod}}$, which we for the

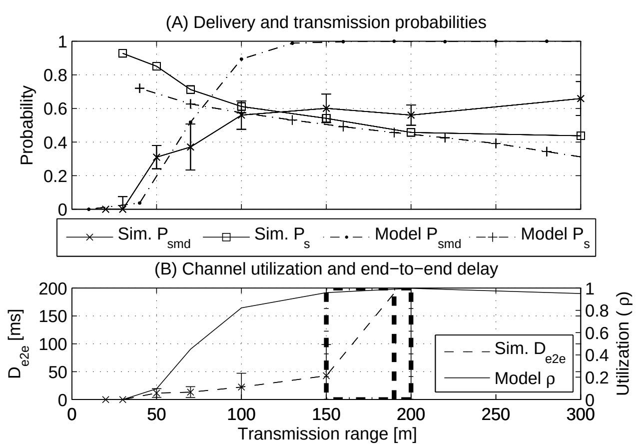

Figure 5. Model vs. simulation for varying tx ranges for $\sigma = \frac{1}{30}\,\frac{nodes}{m}$

model define as the range of points that are within 0.01 of the maximum $P_{\text{smd}}^{\text{mod}}$, and for the simulation as the mean values that overlap the confidence bounds of the maximum mean $P_{\text{smd}}^{\text{sim}}$. The values typeset in bold denote the points that are considered the optimal choices, when only considering the P_{smd}.

For both the model and simulation it can be seen that when contention is low ($\sigma < \frac{1}{20}\,\frac{nodes}{m}$), the optimal range extends to the longest tx ranges of $300\,m$, whereas in the high contention cases ($\sigma = \frac{1}{20}\,\frac{nodes}{m}$), P_{smd} drops before reaching ranges of $300\,m$. In these cases, the addition of nodes for longer transmission ranges does not compensate the corresponding drop in P_{s}. From the simulation results we further see that except for the cases $(1, 40, 10)$ and $(2, 20, 10)$, the range of optimal points covers a wide range. This suggests, as indicated in fig. 5 (A), that within some range of the highest values of P_{smd}, the sensitivity to variation of *tx power* is low. The simulation results in tab. I further show that in

Setting	Model		Simulation	
$tx\ rate, \frac{1}{\sigma}, f_{\text{bc}}$	$\mathbf{opt}\,[m]$	$P_{\text{smd}}^{\text{mod}}$	$\mathbf{opt}\,[m]$	$P_{\text{smd}}^{\text{sim}}$
(1, 40, 10)	$\mathbf{> 170}$	0.9981	**300**	0.70($\pm$0.08)
(2, 40, 10)	$\mathbf{> 170}$	0.9981	**150**,300	0.88($\pm$0.06)
(2, 30, 10)	$\mathbf{> 160}$	0.9969	100..**300**	0.65($\pm$0.10)
(2, 20, 5)	**150**..270	0.9920	**70**..200	0.60($\pm$0.08)
(1, 20, 10)	**150**..270	0.9920	100, **200**	0.20($\pm$0.08)
(2, 20, 10)	**150**..270	0.9920	**150**	0.44($\pm$0.10)

Table I
TX RANGE FOR OPTIMAL P_{SMD} FOR SIMULATION AND MODEL.

low contention cases, a higher *tx rate* generally leads to a higher P_{smd}. This can be explained by the fact that hidden nodes have less time to cause collisions with shorter frame transmission time. A similar effect is not seen in the model as the MAC submodel does not consider hidden nodes to derive P_{col}. In the following we evaluate the channel utilization model. However, since the P_{smd} model does not take correlated collisions into account, we compensate our model and use $\lambda = f_{\text{bc}}(1 + (N_{\text{zone}} - 1)P_{\text{smd}}\mathbf{P_{col}})$.

Fig. 5 (B) shows how $D_{\text{e2e}}^{\text{sim}}$ increases due to an increasing level of contention as tx power increases. In this case, the $D_{\text{e2e}}^{\text{sim}} < 160\,ms$ requirement is exceeded in the interval $150-200\,m$ where the network saturates, causing queue instability. The channel utilization model estimates the saturation point ($\rho \sim 1$) at $190\,m$. Revisiting the discussion regarding hidden nodes in section II-C, the results show that the considered estimate of μ seems reasonable.

Fig. 6 show optimal *tx power* and actual P_{smd} and D_{e2e} for all cases, considering 3 tx power selection schemes. 'default' is a fixed default setting of $60\,mW$ used in the PRISM 802.11b chipset, also modelled in ns-2. Using this scheme, the $D_{\text{e2e}}^{\text{sim}} < 160\,ms$ requirement is exceeded in most cases except when contention is low in (2,40,10). Clearly, this fixed default tx power is unsuitable for the considered mp-to-mp broadcast. Turning attention to optimization options, two schemes are considered: 'model' uses the presented models for estimating P_{smd} and ρ, and 'simulation' is based on P_{smd} and D_{e2e} from simulation results alone.

In terms of optimization, we first consider the *tx rate* in relation to the tradeoff II between lower contention and higher robustness mentioned in sec. I. The results for $(x, 40, 10)$ and $(x, 20, 10)$ clearly show that increasing tx rate leads to improved P_{smd}, whereas lower tx rate, i.e. more robust modulation scheme, is not beneficial. This is a consequence of collisions and not fading being the main cause of losses.

Focusing the analysis on optimization of *tx power*, we first study the baseline results achieved from 'simulation' in fig. 6. The optimal tx power varies between approximately $1 - 10\,mW$, which clearly shows the need for tx power adaptation to ensure maximisation of P_{smd} within the delay requirements. To establish the capabilities of the cross-layer model to provide optimal results, we consider the results for 'model'. In all cases except $(1, 40, 10)$, the obtained P_{smd} values are similar for model and simulation and D_{e2e} is well below the limit in all cases. Overall, this shows that the proposed model is in most cases suited for determining tx power settings that lead to practically optimal P_{smd}.
The exception here is $(1, 40, 10)$ where a lower P_{smd} is obtained due to the channel utilization model being slightly conservative. Interesting is also the case $(2, 20, 5)$, where similar P_{smd} values are obtained for very different tx powers. In the simulation result in tab. I, the optimal range spans from $70 - 200\,m$, meaning that the selection of tx power within this range mainly influences D_{e2e}, which is also clear from fig. 6.

Considering the results in tab. I, we see that the optimal range of the simulation results, except $(1, 40, 10)$ and $(2, 20, 10)$, include the $150\,m$ tx range. This indicates that a simple optimization scheme having a default tx range of $\sim 150\,m$ combined with a channel utilization model to prevent saturation, would yield acceptable results in most cases. However, model improvements and further studies of cases for other tx rates and densities are needed to determine if a P_{smd} model does give a significant benefit. Finally, this aspect should be considered for other broadcasting schemes that are needed anyway in order to satisfy the P_{smd} requirements.

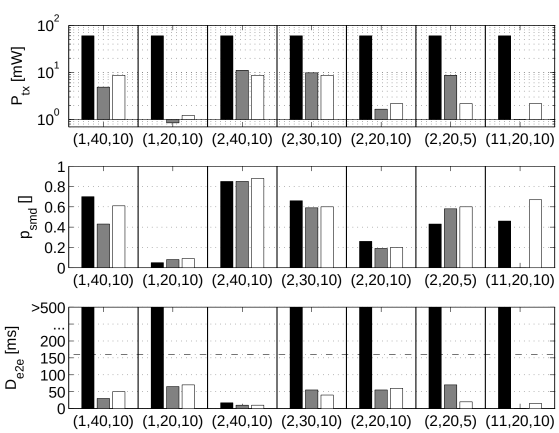

Figure 6. Tx power, P_{smd} and D_{e2e} for different configurations. Bars represent: 'default' (black), 'model' (dark gray), 'model+simulation' (light gray), and 'simulation' (white). Notice: No $11\,\frac{Mbit}{s}$ support in model.

V. Conclusion and Future Work

This work has considered a model-based cross-layer optimization of PHY layer parameters *tx rate* and *tx power* to reduce end-to-end delay and increase the successful message reception probability in a broadcast setup. It is shown that tx power adaptation is needed to reduce contention for varying densities but may have a less significance in low contention scenarios. Our proposed flooding broadcast model assumes independent losses, however, it is shown that correlated losses due to collisions impact message reception probabilities greatly; even in low contention scenarios. Finally, a heuristic channel utilization model for estimating network saturation has been proposed. Altogether, our studies have shown good correlation between results of ns-2 based simulations and the cross-layer model.

Clearly, flooding broadcast is a simple but inefficient broadcasting scheme. In practice, other broadcasting schemes, e.g. AHBP [9] should be considered in future work. Also, in the considered cases, simulation and model results have indicated that a good choice of transmission range is $\sim 150\,m$. Additional work is needed to determine if this result can be generalized, particularly in relation to other broadcasting schemes.

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