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**Wireless Personal Area Networks**

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| Response |  |
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1. Introduction

Here a proposal is presented for a completely distributed transmit power control mechanism for peer aware communications (PAC) at the physical (PHY) layer, including prioritized communications (at PHY layer), for any number of transmit/receive (Tx/Rx) source/destination pairs (single-hop) or source/relays/destination pairs (multi-hop).

The power control mechanism is a refinement of distributed discrete SINR balancing as described in [1][[1]](#footnote-1), by incorporating game-theoretic utility maximization, in order to obtain Pareto optimal outcomes, rapidly. It offers better packet delivery ratio (PDR) for high priority communications in less iterations/time-stages than conventional power control techniques that can be applied in a distributed fashion. Moreover, the proposal reduces power consumption across all sources, significantly.

The power control mechanism is an improvement and simplification of the game presented in [3], whereby the proposed mechanism here is significantly easier to implement than that method described in [3]; and as opposed to the method described here, the method in [3] does not consider prioritized communications

This mechanism requires no communications amongst source/destination groups that take part in the game[[2]](#footnote-2) – although paired sources that are discovered in the MAC (or potentially PHY) given different schedules at the MAC, for instance, may not take part in the game. Those source/destination pairs (or equivalently players) that take part in the game can be considered as hidden terminals to each other.

Importantly this mechanism allows for implementation of prioritized communications at the PHY layer – where we consider three priorities for communications *low priority*, *medium priority* and *high priority* communications. It is anticipated in typical PAC that low priority communications will be most prevalent, with medium priority communications next most prevalent and high priority communications the least prevalent. It should be highlighted that although the mechanism is presented for three priority levels, it can be extended to any number of priority levels. [[3]](#footnote-3)

1. Packet Delivery Ratio (PDR) modeling

Accurate modeling of packet delivery ratio (PDR, *PD*), for typical peer-aware communications as a compressed exponential function of inverse signal-to-interference+noise ratio (SINR, ) is a key component of implementation of the power control mechanism here. Hence PDR can be expressed as

 . (1)

Where *ac* and *bc* are constant parameters that depend upon the type of modulation, packet size, coding scheme coding rate, packet size and data rate, ** is defined as

, (2)

where *Pt,i*is transmission power of source node-of-interest *i*, *Pt,j*is transmission power from source-interferers *j* = 0,..,*N-1*, *j≠i*, to node i, is channel gain from source-to-destination of pair *i*, is channel gain from interfering sources-*j* to non-paired destinations *i* and *Pnoise* describes additive white gaussian noise (AWGN).,

And PDR *PD* is related to packet error rate (PER) simply as

*PD*= 1 – PER. (3)

The first described accurate modeling of PDR as a compressed exponential function for IEEE 802.11g Standard [5] type data rates and packet sizes, modulations and coding schemes is described in [3]. Where the PDR modeling results in [3], are shown to be a very accurate match for five packet-size/data-rate pairs with respect to the 802.11g Trivellato simulator results [6].

Here we show accurate modeling of PDR, *PD*, in the form of (1) according to PER results as a function of *Es/N0* in 802.15.8 *DCN 13-58r1* [7] suitable to PAC, where the interpretation of these results in terms of either signal-to-noise-ratio (SNR) or SINR, **, is described in DCN *13-169r1* [8] . Here we assume interference+additive white gaussian noise can be considered as aggregate noise as in [8]. According to [8] SINR, **, in terms of *Es/N0* as

(4)

Where *Tsym*is the symbol period and *Ts* is the inherited sample time, and the ratio of *Tsym*/*Ts* is assumed to be fixed to 3 as in [8]. Applying the results for packet size of 150 bytes and convolution code in *DCN 13-58r1* [7], with 9 different modulation types/code sizes to provide accurate simulation results for PER, then according to eqns. (1), (3) and (4), we obtain 9 particular values respectively for the two parameters *ac* and *bc* used to specify PDR and these are given in Table I on the following page.

**Table 1,** Parameter values *ac* and *bc* according to expression for PDR in terms of inverse SINR ** for eqn (1), with respect to fitting to results for Es/N0 (and hence **) described in [7] for PAC for packet sizes of 150 bytes[[4]](#footnote-4)

|  |  |  |
| --- | --- | --- |
| Modulation and Coding Rate | *ac* | *bc* |
| BPSK rate 1/2 | 3.891 | 8.85 |
| BPSK rate 3/4 | 2.13 | 9.48 |
| QPSK rate 1/2 | 1.95 | 9.02 |
| QPSK rate 3/4 | 1.066 | 9.29 |
| 16-QAM rate 1/2 | 0.62 | 8.31 |
| 16-QAM rate 3/4 | 0.275 | 8.45 |
| 64-QAM rate 2/3 | 0.125 | 8.34 |
| 64-QAM rate 3/4 | 0.085 | 7.81 |
| 64-QAM rate 5/6 | 0.06 | 8.034 |

For the purposes of easier analysis and implementation in the distributed power control mechanism described in this proposal, the PDR in (1) can be restated in terms of SINR as

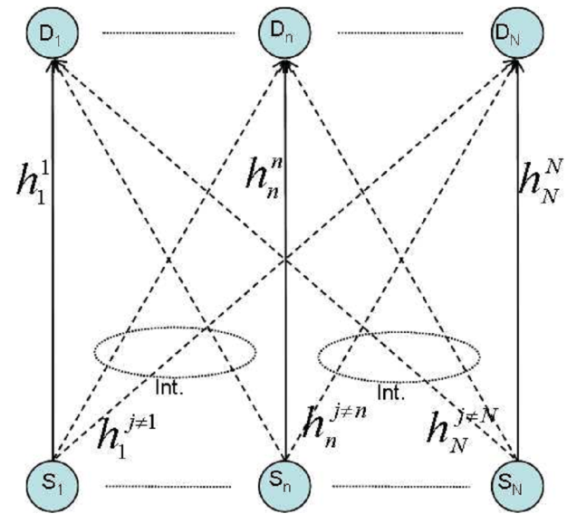
(5)

For any packet sizes *Mp* other than 150 bytes, according to *tg8* simulation specification in *DCN 13-99r2* [9], eqn. (5) can then be amended to

 (6)

3 System Model Scenarios

3.1 Single-Hop Scenario



**Figure 1:** Logical topology for single-hop communications, showing *i* = 1,… *N*, *N* sources S*i*, *N* Destinations D*i*, *N* target channel gains[[5]](#footnote-5) – solid lines; and *N*(*N*-1) interfering channel gains – dashed lines, *j* = 1,…,*N*, *j*≠*i*.

For the single-hop scenario for the distributed power control mechanism here, a logical topology is shown above in **Figure 1**. The distributed power control occurs across *N* source/destination pairs, considered as players in the game. Here each source transmits directly to one receiver/destination with direct single-hop communication. An AWGN channel with static fading, or slow frequency-nonselective fading (which may be Rayleigh fading, but also could also be slow fading described by other distributions, e.g., Ricean, Nakagami-m, gamma). For slow fading it is assumed the Doppler spread is significantly less than the packet transmission rate for any Tx to Rx.

In the single-hop scenario distributed power control mechanism, each source *Si* acts as a hidden terminal to Destinations *Dj≠i*and it is assumed across each of the iterated stages **, ** = 1,…,*T* (where *T* is finite number of stages over which the power control takes place) that every source creates non-negligible interference to non-target destinations.

The aim is to minimize Tx power and obtain target PDR (equivalently target SINR,t,i). With three priorities of communications as described in Section 1, the method to achieve this is by implementing the power control mechanism to be subsequently described, seeking to achieve three separate PDR targets (*pdt-high, pdt-medium, pdt-low*) to enable prioritized communications. A typical instantiation (which an implementation is not restricted to) – could be as given below:

(7)

It is assumed that on any occasion of playing the game, that during the iterated running of the power control mechanism that for any player *i*, their communications priority does not change from the ** = 1 to ** = T. The mechanism supports from *N* = 2 Tx/Rx pairs up any number *N* of pairs (equivalently players).

## 3.2 Multi-Hop Scenario

S1

D1

S2

R2,M

D2

SN

RN,1

DN

RN,M

R2,1

R1,1

R1,M

SN

RN,1

**Figure 2**: Logical topology for multi-hop (*M*+1)-hop communications, with *i* = 1,… *N*, *N* sources *Si*, *N* Destinations *Di*, *N×M* Relays *Ri,m*, *m* = 1,…,M . Solid lines denote target channels for node groups, dotted lines denote interference channels.

For the multi-hop scenario for the distributed power control mechanism here, a logical topology is shown above in **Figure 2**. There are *N×(M*+1)target channel gains[[6]](#footnote-6) , *m* = 1,…, *M+*1, and *N× (M+1) ×* (*N*-1) interfering channel gains , *j* = 1,…,*N*, *j*≠*i.* It is assumed that in each iterated stage of power control, that only interfering sources, or interfering relays, interfere for the same *m*th hop – this is enabled by separating each hop transmission, for the multi-hop scenario here, into different time slot periods[[7]](#footnote-7) *s* = 1,…(*M*+1), giving*s*, with respect to any particular stage of power control implementation ** (as ** is described for single-hop in the previous subsection) . E.g., With *M* = 1 relays, and (*M*+1)=2 hops, on the 2nd hop, all relays *Ri≠j,1* only provide interference to target destination *Di* (in the second hop there is no effect from 1st hop interference from sources *Si≠j*) – thus each *D*i only experiences the combined effect of (*N*-1) interfering channels emanating from *Ri≠j,1*.

The cases of static fading and slow flat fading are the same in the multi-hop scenarios as for the single-hop scenario, as well as the previous descriptions with respect to priorities and the stated aims of the distributed power control are the same. Further there are two types of wireless communications for which the multi-hop scenario is valid for the power control mechanism here:

## 3.2.1 (i) Decode-and-forward communications; (ii) Detect-and-Forward communications

In i) at each target relay the received signal is demodulated and decoded. Whereas in ii) at each target relay the received signal is demodulated (but not decoded). Clearly in ii), without decoding at target relays there is greater error propagation. However (ii) allows for less complex hardware.

With (i) and (ii), as for single-hop it is assumed the communications maintain the same priority same target *pdt,i* for a particular player *i* on any stages** of particular stages of implementing the power control mechanism. Further with (i), the same target *pdt,i* is maintained for each hop *m* = 1,…,*M*+1, reaching each target SINR *t,i*,*Dec-F* which is equivalent to *t,i* for a single-hop can be expressed in terms of target PDR (following from eqn (6)) as:

(8)

where ln(.) denotes the natural logarithm. However with detect and forward, without decoding, explicitly attempting to reach the specific *pdt,i* is not feasible – but the power control mechanism can still be enabled if it is considered that any particular coding scheme has a particular coding gain, which means we can adapt a target SINR *t,i*,*,m,Det-F* according to the expected error propagation, according to only demodulating, but not decoding. To best obtain *pdt,i*  at the destination, in detect and forward we can simply scale what *t,i*, would be for a single-hop in (8) by the expected coding gain (*cg*-dB) [[8]](#footnote-8)that is lost due to only demodulating – this error propagates through the *M* relays and is additive in the dB-domain according to how many relays are used. However simply for *M* = 1 relay, two hops, the target SINR at *Ri* and *Di* *i*, becomes for detect-and-forward

(9)

1. Formal Description of Power Control Mechanism

The power control mechanism is in the form of a game that refines discrete SINR balancing.. A transmit power is assumed from a discrete available transmit power levels vector **P***vec*:

**P***vec* ϵ (0, 1W] for the 2.4 GHz and 5.7 GHz bands

**P***vec* ϵ (0, 1mW] band A,D, (0, 20 mW] band B, (0, 250 mW] band C of sub-1GHz band for Japan

It is assumed that **P***vec* contains a finite number of possible power levels, e.g., *L=21*, uniformly spaced in the dB-domain. In single-hop communications, each source node *i* transmits at power level *Pt,i*(**) at each time slot **∈ (1,…*T*), where the choice of *T* is according to when it is estimated that the algorithm has finally converged to an optimal solution. And, without loss of generality for multi-hop communications, within hop periods, at each time slot *s, s* = 1,…,*M*+1, source (or relay) node *i* transmits at *Pt,i*(*s*)[[9]](#footnote-9).

* 1. Algorithm for Power Control Mechanism

**At** time** = 0; In the initiation of the mechanism: according to communications priority obtain target PDR, typical values as in equation (7) are *pdt,i* =0.99, or 0.95 or 0.9. Then compute equivalent target SINR, *γt,i*, using equation (8) if single-hop or decode-and-forward, or equation (9) if detect-and-forward, and parameters from Table 1.

Initial transmission powers for any source node *i*, ** = 0, *Pt,i*(0), can be chosen randomly from possible ***P****vec* values, or alternately suitably according to priorities of communications.

**At** ** = 0;

i

**From** time ** = 0,…,*T*-1,

 , (10)

where in (10) estimate denominator of received interference + noise power; and numerator, received target signal power , using common methods for SINR estimation such as described in [10-13].

; (11) where is the known transmit power of node *i.*

; (12)

; (13) where  are obtained from Equation (6) and Table 1.

** = **+1;

if ** ≥ 3 ∧ *γi*(*τ-1*)*≈ γi*(*τ-2*) ∧ *Pt,i*(*τ-1*)*= Pt,i*(*τ-2*) ∧ flagi = 1,

flagi = 2**

elseif ** ≥ 2 ∧ *γi*(*τ-1*)*≈ γi*(*τ-2*) ∧ *Pt,i*(*τ-1*)*= Pt,i*(*τ-2*) ∧ flagi = 0,

flagi = 1;

end if

If flagi = 0,

; (14)

else,

;

end if

;

; (15)

, (16), .

; (A vector of length *L* of possible utilities ) (17)

 ; (Find the unique Nash equilibrium point for PD *i*) (18)

. (19)

Transmit *Pt,i*(**) from PD *i* at time slot ** ;

**End** Algorithm at T = **when flagi = 2, **.**

It should be noted that in all of the preceding Algorithm description, it is assumed the power control occurs synchronously across stages ** and PDs *i* = 1,…,*N*; this is not a necessary condition, as this distributed power control can also occur asynchronously.

1. References

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1. The method in [1] is an extension of the constrained power control described in [2]. [↑](#footnote-ref-1)
2. The terms game and mechanism will be used interchangeably throughout this document. [↑](#footnote-ref-2)
3. In IEEE 802.11e there is a mechanism at the MAC layer to apply prioritized communications - namely the Enhanced Distributed Coordination Function (EDCF) that is applied at the MAC layer in IEEE 802.11 which provides prioritized contention-based channel access [4]. [↑](#footnote-ref-3)
4. Where we note the largest root-mean-square error (of all 9 parameter fits) is 0.0021 between this PDR approximation and simulation results in [7]. [↑](#footnote-ref-4)
5. For a static channel, channel gain is the inverse of path loss, for a slow fading channel, the mean channel gain is the inverse of the mean path loss. [↑](#footnote-ref-5)
6. For a static channel, channel gain is the inverse of path loss. For a slow fading channel, the mean channel gain is the inverse of the mean path loss. [↑](#footnote-ref-6)
7. This condition is employed for the means of more clear simulation analysis, and is not a restrictive condition. [↑](#footnote-ref-7)
8. The typical coding gain of a convolutional code, for a code as described in [7]. [↑](#footnote-ref-8)
9. Time slot *M*+1, *s*=*M*+1, is assumed to precede time slot (**+1)1, *s*=1, for multi-hop communications. [↑](#footnote-ref-9)