

# Multiple Access in Ad-Hoc Wireless LANs with Noncooperative Stations

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**Abstract.** A class of contention-type MAC protocols (e.g., CSMA/CA) relies on random deferment of packet transmission, and subsumes a deferment selection strategy and a scheduling policy that determines the winner of each contention cycle. This paper examines contention-type protocols in a noncooperative ad-hoc wireless LAN setting, where a number of stations self-optimize their strategies to obtain a more-than-fair bandwidth share. Two scheduling policies, called RT/ECD and RT/ECD-1s, are evaluated via simulation. It is concluded that a well-designed scheduling policy should invoke a noncooperative game whose outcome, in terms of the resulting bandwidth distribution, is fair to non-self-optimizing stations.

## 1 Introduction

Consider  $N$  stations contending for a wireless channel in order to transmit packets. In a cooperative MAC setting, all stations adhere to a common contention strategy,  $C$ , which optimizes the overall channel bandwidth utilization,  $U$ :  $C = \arg \max U(x)$ . In a noncooperative MAC setting, each station  $i$  self-optimizes its own bandwidth share,  $U_i$ :  $C_i^* = \arg \max U_i(C_1^*, \dots, C_{i-1}^*, x, C_{i+1}^*, \dots, C_N^*)$ .  $C_i^*$  is a *greedy* contention strategy and  $(C_1^*, \dots, C_N^*)$  is a *Nash equilibrium* [3] i.e., an operating point from which no station has incentives to deviate unilaterally. Note that noncooperative behaviour thus described is *rational* in that a station intends to improve its own bandwidth share rather than damage the other stations'. This may result in unfair bandwidth shares for stations using  $C$ . For other noncooperative wireless settings, see [1,4].

In ad-hoc wireless LANs with a high degree of user anonymity (for security reasons or to minimize the administration overhead), noncooperative behaviour should be coped with by appropriate contention protocols. A suitable communication model is introduced in Sec. 2. The considered contention protocol under the name Random Token with Extraneous Collision Detection (RT/ECD) involves voluntary deferment of packet transmission. We point to the logical separation of a deferment selection strategy and a scheduling policy that determines the winner in a contention cycle. Sec.

3 outlines a framework for a noncooperative MAC setting. A scheduling policy called RT/ECD-1s is described in Sec. 4 and evaluated against the RT/ECD policy in terms of the bandwidth share guaranteed for a cooperative (c-) station (using  $C$ ) in the presence of noncooperative (nc-) stations (using  $C_i^*$ ). Sec. 5 concludes the paper.

## 2 Noncooperative MAC Setting with RT/ECD

Our 'free-for-all' communication model consists of the following non-assumptions:

- neither  $N$  nor stations' identities need to be known or fixed,
- except for detecting carrier, a station need not interpret any packet of which it is not an intended (uni- or multicast) recipient.

This allows for full encryption and/or arbitrary encoding and formatting among any group of stations. To simplify and restrict the model we assume in addition

- single-hop transfer of packets with full hearability, and
- a global slotted time axis.

Any station is thus able to distinguish between v- and c-slots sensed (for 'void' and 'carrier'). An intended recipient of a successful transmission recognises also an s-slot (for 'success') and reads its contents. This sort of binary feedback allows for *extraneous collision detection* in the wireless channel as employed by the following RT/ECD protocol (Fig. 1). In a protocol cycle, a station defers its packet transmission for a number of slots from the range  $0..D-1$ , next transmits a 1-slot *pilot* and senses the channel in the following slot. On sensing an s-slot containing a pilot, any intended recipient transmits a 1-slot *reaction* (a burst of non-interpretable carrier), while refraining from reaction if a v- or c-slot is sensed. A reaction designates the sender of a successful pilot as the winner and prompts it to transmit its packet in subsequent slots; a v-slot will mark the termination of this protocol cycle. If pilots collide, no reaction follows and the protocol cycle terminates with a no-winners outcome. In a full-hearability environment, RT/ECD operates much like CSMA/CA in the IEEE 802.11 Distributed Coordination Function [2], with the pilot/reaction mechanism resembling the RTS/CTS option. Note, however, that it is to provide ACK functionality rather than solve the hidden terminal problem; moreover, pilots only need to be interpreted by intended recipients, while reactions are non-interpretable.

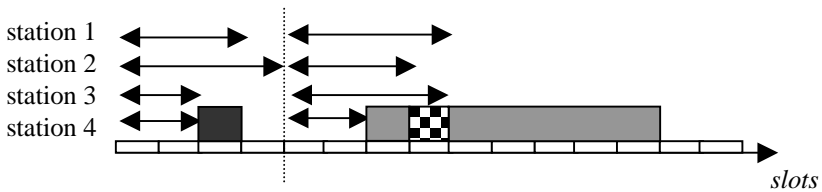


Fig. 1. RT/ECD, a no-winners protocol cycle followed by one where station 4 wins

To account for noncooperative behaviour, we assume that

- $NC$  out of  $N$  stations are nc-stations that may use greedy deferment selection strategies ( $NC$  need not be known or fixed),
- the c-stations use a standard deferment selection strategy  $S$ , defined by the probabilities  $\pi_l$  of selecting a deferment of  $l$  slots ( $l \in 0..D-1$ ), and
- all stations adhere to a common scheduling policy.

A simple greedy strategy might consist in introducing a downward  $bias \in 0..D-1$  to the deferment distribution e.g.,  $\pi_0' = \pi_0 + \dots + \pi_{bias}$  and  $\pi_l' = \pi_{l-bias}$  for  $l > 0$ . As shown in Sec. 4, this may leave the c-stations with a tiny fraction of the bandwidth share they would obtain in a cooperative setting (with  $NC=0$ ).

### 3 Framework for a Noncooperative MAC Setting

Besides pursuing a greedy deferment selection strategy, an nc-station might try various 'profitable' departures from the protocol specification – for example, pretend to have transmitted a pilot and sensed a reaction. In RT/ECD-like protocols, however, such cheating must involve making false claims as to the presence or absence of carrier on the channel, which is easily verifiable. Therefore it suffices to design a scheduling policy so as to minimise the benefits of any conceivable greedy strategy vis-a-vis  $S$ . A greedy strategy can be expected to be

- *isolated* i.e., not relying on collusion with other nc-stations, and
- *rational*, meaning that deferment selection rules observed to increase own bandwidth share are more likely to be applied in the future, however, to stay responsive to a variable environment, no rules are entirely abandoned [3].

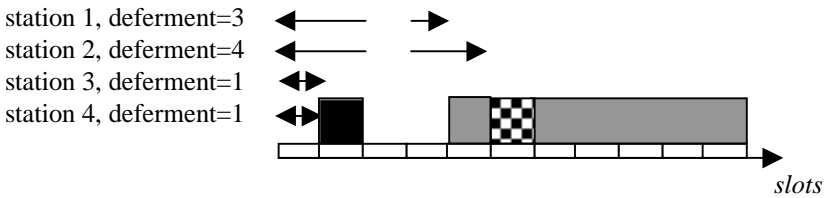
A reasonable scheduling policy is constrained to be

- *nontrivial*, in that no deferments should be known a priori to render other deferments non-winning (note that RT/ECD is a counterexample, deferment of length 0 being 'fail-safe'), and
- *incentive compatible*, in that channel feedback up to any moment in the deferment phase should not discourage further pilots (as a counterexample, imagine a scheduling policy whereby a second-shortest deferment wins).

Let  $U_c(NC)$  be the bandwidth share obtained by a generic c-station in the presence of  $NC$  nc-stations. A fair and efficient scheduling policy is one that ensures  $U_c(NC) \geq U_c(0) \geq U_c(0)|_{RT/ECD}$  for any  $NC$  and any greedy strategy, where ' $\geq$ ' reads 'not less or at least tolerably less than.' This means that the presence of nc-stations should not decrease a generic c-station's bandwidth share by an amount that its user would not tolerate. The latter 'inequality' implies that protection against nc-stations should not cost too much bandwidth in a cooperative setting, RT/ECD being a reference policy supposed, by analogy with IEEE 802.11, to perform well in a cooperative setting.

### 4 Evaluation of the RT/ECD-1s Scheduling Policy

While RT/ECD prevents any station from winning if a collision of pilots occurs, in RT/ECD-1s the first successful pilot wins no matter how many collisions precede it. A protocol cycle is illustrated in Fig. 2. A slot occupied by a pilot (or a collision of pilots) is paired with a following one, reserved for reactions. Stations whose pilots were not reacted to back off until the next protocol cycle. The lack of a second chance to transmit a pilot in the same protocol cycle creates a desirable ‘conflict of interest’ for an nc-station selecting its deferment. RT/ECD-1s is arguably nontrivial and incentive compatible. (A family of similar policies can be devised whereby the  $n^{\text{th}}$  successful pilot wins, or the last one if there are less than  $n$ ; of these, RT/ECD-1s yields the best winner outcome vs. scheduling penalty tradeoff.)



**Fig. 2.** RT/ECD-1S protocol cycle: stations 3, 4 back off when no reaction follows; station 1’s first successful pilot wins (deferments are frozen during reaction slots)

In a series of simulation experiments, simple models of c- and nc-stations were executed to evaluate RT/ECD-1s against the backdrop of RT/ECD. In each simulation run,  $D=12$ ,  $N=10$  and  $NC \in 0..N-1$  were fixed and packet size was 50 slots. Symmetric heavy traffic load was applied with one packet arrival per station per protocol cycle. The strategy  $S$  at the c-stations used a truncated geometric probability distribution over  $0..D-1$  i.e.,  $\pi_i = \text{const.} \cdot q^i$  with parameter  $q=0.5$ , 1 or 2 (referred to symbolically as ‘aggressive,’ ‘moderate’ and ‘gentle’). Two isolated and rational greedy strategies were experimented at nc-stations: Biased Randomiser (BR) and Responsive Learner (RL). The former introduced a downward bias as explained in Sec. 2; the *bias* value was optimised on the fly at each nc-station and occasionally wandered off the optimum to keep the strategy responsive to possible changes in other stations’ strategies. The latter mimicked so-called *fictitious play* [5] by selecting deferments at random based on their winning chances against recently observed other stations’ deferments. Once selected, a deferment was repeated consistently throughout the next update period of  $UP=20$  protocol cycles. For simplicity, strategies were configured uniformly within all stations of either status, producing two noncooperative game scenarios:  $S$  vs. BR and  $S$  vs. RL.

Ideally,  $U_c(NC) \equiv 1/N$  of the channel bandwidth. Scheduling penalties cause this figure to drop even in a cooperative MAC setting (at  $NC=0$ ), whereas nc-stations may bring about a further decrease. For the  $S$  vs. BR scenario, Fig. 3 (*left*) plots  $U_c(NC)$  (normalised with respect to  $1/N$ ) as measured after the nc-stations have

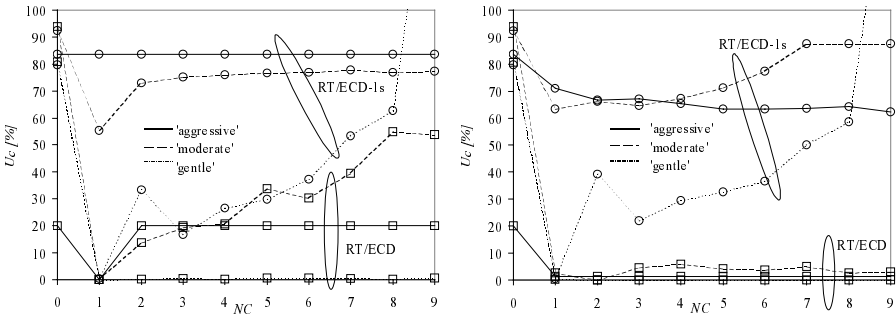


Fig. 3. C-station bandwidth share as a function of  $NC$ , left:  $S$  vs.  $BR$ , right:  $S$  vs.  $RL$

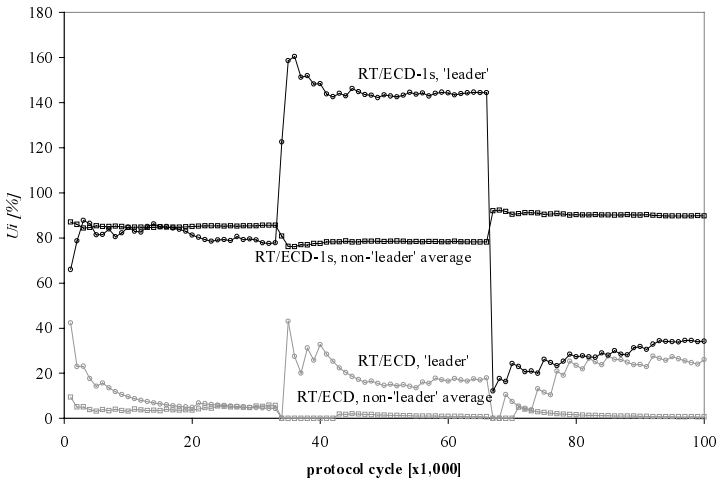


Fig. 4.  $RL$  vs.  $RL$ : Stackelberg 'leader' scenario

reached a Nash equilibrium with respect to *bias*. Note that while  $RT/ECD-1s$  is generally superior to  $RT/ECD$ , much depends on the parameter  $q$ : the 'gentle' value is not recommended, especially for a small  $N$ , while for the 'aggressive' value, the  $nc$ -stations detect that the optimum *bias* is 0, hence  $U_c(NC)$  remains constant. Also,  $RT/ECD-1s$  has difficulty coping with  $NC=1$ . Fig. 3 (right) presents similar results for the  $S$  vs.  $RL$  scenario. Observe that under  $RT/ECD-1s$ ,  $nc$ -stations' increased intelligence does not worsen  $U_c(NC)$  significantly, which it does under  $RT/ECD$ . Again, much depends on  $q$ : although the 'moderate' value pays off in a cooperative setting, the 'aggressive' value offers more uniform guarantees for  $U_c(NC)$  across various  $N$ . Lose-lose situations (with both the  $c$ - and  $nc$ -station bandwidth shares below  $U_c(0)$ ) were observed under  $RT/ECD$  owing to this policy not being nontrivial.

Fig. 4 presents an  $RL$  vs.  $RL$  scenario where, after a third of the simulation run, one  $nc$ -station captures more bandwidth by lengthening its update period tenfold

whenever a deferment of length 0 is selected. In doing so, it becomes a so-called Stackelberg 'leader' [5]. A form of protection, switched on after another third of the simulation run, is for a c-station to monitor its own and other stations' win counts over the last update period. If the former is zero and the latter nonzero, the station temporarily resorts to  $S$  with the 'aggressive'  $q$ . Under RT/ECD-1s, this quickly results in the 'leader' obtaining a less-than-fair bandwidth share. Under RT/ECD the protection is ineffective; moreover, the overall bandwidth utilisation remains poor.

## 5 Conclusion

Ad-hoc wireless LAN systems, with their preferences to user anonymity and a lack of tight administration, potentially constitute a noncooperative MAC setting. For a class of contention protocols relying on random deferment of packet transmission, c-stations are vulnerable to unfair treatment by nc-stations, which use greedy deferment selection strategies. The design of a scheduling policy has been shown to be quite sensitive in this respect. A framework for a reasonable scheduling policy and greedy strategies that might be expected from nc-stations has been outlined. A slotted-time scheduling policy called RT/ECD, analogous to CSMA/CA with the RTS/CTS option, and an improved variant thereof called RT/ECD-1s have been evaluated under heavy load to find that the latter guarantees the c-stations a substantially higher bandwidth share. This it does assuming that nc-stations behave rationally and seek a Nash equilibrium. In the experiments, RT/ECD-1s coped well with nc-stations using a randomisation bias or a fictitious play-type greedy strategy.

Several directions can be suggested for future work in this area:

- a game-theoretic study of RT/ECD-like scheduling policies aimed at establishing the mathematical properties of the underlying noncooperative games,
- model extensions to include multihop wireless LAN topologies (in particular, dealing with the problem of hidden stations); development of a suitable extension of RT/ECD-1s is under way, and
- access delay analysis to investigate the issues of QoS support.

## References

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