Basic Client Relay Model for Wireless Cellular Networks

Sergey Andreev
Tampere University of Technology
Tampere, FINLAND
Email: sergey.andreev@tut.fi

Olga Galinina
Speech Technology Center
St. Petersburg, RUSSIA
Email: olga.galinina@gmail.com

Andrey Turlikov
St. Petersburg State University
of Aerospace Instrumentation
St. Petersburg, RUSSIA
Email: turlikov@vu.spb.ru

***Abstract*—The paper considers cellular networks, where clients may cooperate to relay packets for each other. Client relay technology is a cross-layer channel-aware technique that may dramatically improve throughput, energy efficiency, and delay performance of modern and future wireless networks, such as IEEE 802.16m and LTE-Advanced. The proposed basic system model is the simplest client relay scenario under realistic assumptions. We obtain an accurate closed-form estimation on mean packet delay for all the source nodes within this model and verify the results by means of simulation.**

Keywords: wireless cellular networks, mean packet delay, data relaying, client cooperation.

I. Introduction

Wireless networks demonstrate worldwide proliferation, which has advanced recently with the introduction of the novel communication technologies [1], [2]. However, the future success of the wireless communication significantly depends on the solution to overcome the disproportion between the requested *quality of service* (QoS) and limited network resources.

Spectrum is a natural resource that cannot be replenished. As such, the need for its effective use introduces the problem of *spectral efficiency*. On the other hand, *energy efficiency* is also becoming increasingly important primarily for small form factor mobile devices due to the growing gap between the available and the required battery capacity, which is demanded by the ubiquitous multimedia applications [13].

For the above reasons, resource allocation and management becomes critical for technologies, where multiple clients share the limited wireless spectral resources. Currently, the layered architecture dominates in networking design and each layer is operated independently to maintain transparency. Among these layers, the *physical* (PHY) layer is responsible for the raw-bit transmission, whereas the *medium access control* (MAC) layer arbitrates access of clients to the shared wireless resources.

However, wireless channels are commonly known to suffer from multipath fading. To make matters worse, the statistical channel characteristics of different clients are typically different. Therefore, traditional layer-wise architecture turns out to be inflexible and results in the inefficient wireless resource utilization. An integrated and adaptive design across different layers is thus required to overcome this limitation. As a consequence, *cross-layer* optimization across PHY and MAC layers is desired.

Enabling cross-layer optimization, so-called *channel-aware* approaches are introduced and developed to take into account wireless *channel state information* explicitly. They exploit interactions between different layers and may significantly improve system performance as well as adaptability to service, traffic, and environment dynamics [20], [14], [11]. Among these, cross-layer optimization for throughput improvement has long been a popular research direction [21].

However, as wireless clients become increasingly mobile, the focus of recent efforts tends to shift toward energy consumption at all layers of communication systems [5], from architectures [6] to algorithms [19]. Recently, cross-layer *cooperative* techniques receive increasing attention [15], [16] to take advantage of statistical differences between the clients and thus improve the performance of a wireless network.

II. Research Background

As more clients need to share the same spectrum for broadband multimedia communications and cellular networks move toward aggressive full-frequency reuse scenarios [1], [2], the performance of modern wireless networks is heavily impaired by interference. Since wireless is broadcast, the transmission of one client interferes with that of neighboring clients and consequently reduces energy efficiency. However, clients can gain in energy efficiency, if cooperation among neighboring clients is allowed. Hence, spatial domain resource management is important to control the behavior of clients at different spatial locations [3].

On the other hand, cooperation requires additional signaling overhead and consumes extra energy. Cooperation can also cause transmission delay that may impact throughput adversely and thus hurt energy efficiency. However, delay can be exploited for energy-efficient link adaptation, as extending transmission duration may improve energy efficiency. Therefore, it is important to investigate all the basic trade-offs associated with relaying and establish the scenarios where cooperative transmission has real benefits for wireless cellular networks.

It has been demonstrated that significant energy savings can be achieved and they grow almost linearly with distance when either transmitter or receiver cooperation is allowed [7]. Furthermore, it is also shown that cooperation can even reduce delay within certain transmission ranges since sometimes

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it enables higher order modulation and increases data rate. Similarly, when receiver cooperation is exploited, significant energy savings can be observed [10].

Besides transmitter and receiver cooperation, *relay* cooperation across neighboring clients is also effective in improving network energy efficiency. Since the energy for reliable data transmission grows exponentially with distance [22], it is more energy efficient to send data using several shorter intermediate hops than using a long hop, if the energy to compute the route is negligible [17]. For these reasons client cooperation is believed to become one of the key technologies for the performance improvement in future cellular wireless networks.

However, client relay incurs delay and energy consumption of relay nodes. Therefore, in some scenarios, it is advantageous to use longer hops [8]. Hence, the optimal selection of relay nodes is a trade-off between source-node performance and relay cost to enhance overall network energy efficiency. In this paper we conduct analytical performance evaluation of the simplest, but nonetheless realistic client relay model, which we call *basic* in what follows. We focus on obtaining an accurate mean packet delay estimation for the source nodes within the model and leave energy efficiency evaluation for the future work.

The rest of the text is structured as follows. In Section III we detail the proposed client relay system model and introduce the notations we use in the rest of the text. Section IV estimates mean packet delay firstly for the system without cooperation. Then the solution for the system without cooperation is extended for the system with cooperation. In Section V we verify the obtained analytical results by means of simulation. Finally, Section VI concludes the paper.

III. System Model and Notations

We consider the simplest relay network topology with two source nodes and one sink node (see Figure 1). The node A is termed the *originator* and generates new data packets with the mean arrival rate λ_A. The node R is termed the *relay* and generates new data packets with the mean arrival rate λ_R. Additionally, the relay may eavesdrop on the packets from the originator and store them for the subsequent retransmission. The node B is termed the *base station* and receives data packet from both the originator and the relay. The base station has no own traffic. The assumptions below detail the system model.

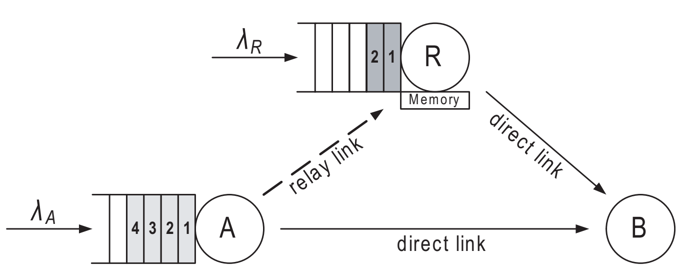

Figure 1. Basic client relay model

1) The system time is discrete. A *slot* is the unity of the system time. All the packets in the system have equal length. The transmission of a packet takes exactly one slot.
2) The number of packet arrivals per slot to the originator and the relay queues are independent and identically-distributed (i.i.d.) random variables with means λ_A and λ_R, respectively. For simplicity of the further analysis we assume *Poisson arrival process*.
3) Both source nodes have queues of infinite capacity to store own data packets. Additionally, the relay node has a memory location to store one eavesdropped packet from the originator for subsequent retransmission.
4) The system is centralized and is scheduled by the base station. A fair *stochastic* round-robin scheduler is considered, which alternates the source nodes accessing the channel with equal probability (see Figure 2 as an example operation for the scenario shown in Figure 1 and no new arrivals). In particular, if both the originator and the relay have pending data packets, one of them is granted the next slot with probability 0.5 and the other one waits. If either node is empty, the base station schedules the loaded node with probability 1. If both nodes have no pending packets, the system is idle. The scheduling information transmission is assumed to be over a separate channel and consumes no resources.

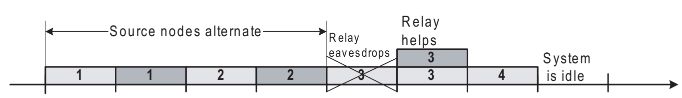

Figure 2. Relay system example operation

5) The channel is error-prone and is based on the multipacket reception (MPR) channel model from [18]. Once transmitted a packet is corrupted with a constant probability, which depends only on the link type and the number of transmitters.

   The basic parameters of the model are:

   - $p_{AB} \triangleq \Pr\{\text{packet from } A \text{ is received at } B \mid \text{only A transmits}\}$
   - $p_{RB} \triangleq \Pr\{\text{packet from } R \text{ is received at } B \mid \text{only R transmits}\}$
   - $p_{AR} \triangleq \Pr\{\text{packet from } A \text{ is received at } R \mid \text{only A transmits}\}$
   - $p_{CB} \triangleq \Pr\{\text{packet from } A \text{ is received at } B \mid \text{A and R cooperate}\}$

   The channel feedback information is assumed to be over a separate channel and consumes no resources. It indicates, whether a packet is received successfully by the base station by the end of the transmission slot. If a packet is corrupted, it is retransmitted by the source. The allowable number of retransmissions is infinite. Nodes are equipped with single transceivers so that they cannot transmit and receive at the same time.
6) Upon the first transmission from the originator the relay successfully eavesdrops on the packet with $p_{AR} > p_{AB}$. If the base station fails to receive this packet from the originator in the current slot with $1 - p_{AB}$ the relay stores it in the memory location for the eavesdropped packet.

7) Upon any retransmission from the originator the relay performs one of the following operations. If the packet being retransmitted by the originator is already stored in the memory location, the relay transmits this packet *simultaneously* with the source and the base station successfully receives the packet with $p_{CB} > p_{AB}$ due to the better quality of the relay link. Otherwise the relay eavesdrops again on the retransmission of the originator and successfully receives the packet with p_{AR}. Once the packet from the originator is received successfully by the base station, the relay frees the memory location for the eavesdropped packets.

Note that the originator is unaware of the cooperative help from the relay. No explicit information is transmitted between the originator and the relay by contrast to [18]. The relay improves the throughput of the originator by sacrificing own energy efficiency. The relay spends additional power when eavesdropping on the originator's packets and transmitting simultaneously with the originator. However, the energy efficiency analysis is kept out of scope of this paper due to the space constraints.

In the most general case the relay may choose either not to eavesdrop on the originator's packets or not to transmit them subject to some relaying policy. We leave such an opportunistic relaying out of scope of this work and restrict the relay to eavesdrop on any transmission from the originator and to transmit originator's packets if stored. In what follows we focus on the most important performance metric of interest: the *mean packet delay* of each source node for the system with and without cooperation. However, the exact derivation of the mean delay value is difficult and we concentrate on estimating it with high accuracy instead.

The analytical approach of this paper exploits the concept of a *service cycle*. A service cycle of a packet is a period of time from the moment the packet is ready for service to the moment its service ends [9]. Generally, service time and service cycle are not equal.

We denote numbers of packets at nodes A and R at the beginning of a slot by Q_A and Q_R, respectively. Also let the mean duration of a service cycle for a packet from A be

$$\tau_{AR} \triangleq \tau_{AR}(\lambda_A, \lambda_R).$$

Then we denote by $\tau_{A0} \triangleq \tau_{AR}(\lambda_A, 0)$ the mean duration of a service cycle for a packet from A conditioning on the fact that $\lambda_R = 0$. Symmetrically, let the mean duration of a service cycle for a packet from R be

$$\tau_{RA} \triangleq \tau_{RA}(\lambda_R, \lambda_A).$$

As such, the conditional mean duration of a service cycle $\tau_{R0} \triangleq \tau_{RA}(\lambda_R, 0)$ may be defined when $\lambda_A = 0$. Clearly, for both systems with and without cooperation it holds

$$\tau_{R0} = \frac{1}{p_{RB}},$$

whereas just for the system without cooperation it also holds

$$\tau_{A0} = \frac{1}{p_{AB}}.$$

We denote the queue load coefficient at node A as

$$\rho_{AR} \triangleq \rho_{AR}(\lambda_A, \lambda_R) = \Pr\{Q_A \neq 0\}.$$

In particular, the queue load coefficient at node A conditioning on the fact that $\lambda_R = 0$ may be established as

$$\rho_{A0} \triangleq \rho_{AR}(\lambda_A, 0) = \lim_{t\to\infty} \frac{N_t\{\text{A transmits}\}}{t} = \lambda_A \tau_{A0},$$

where $N_t\{S\}$ is the number of events S that occurred during the time interval t.

For the system without cooperation ρ_{A0} simplifies to

$$\rho_{A0} = \frac{\lambda_A}{p_{AB}}.$$

Similarly, the queue load coefficient at node R is

$$\rho_{RA} \triangleq \rho_{RA}(\lambda_R, \lambda_A) = \Pr\{Q_R \neq 0\}.$$

Symmetrically, the queue load coefficient at node R conditioning on the fact that $\lambda_A = 0$ may be established as

$$\rho_{R0} \triangleq \rho_{RA}(\lambda_R, 0) = \lim_{t\to\infty} \frac{N_t\{\text{R transmits}\}}{t} = \lambda_R \tau_{R0}.$$

For both systems with and without cooperation ρ_{R0} is

$$\rho_{R0} = \frac{\lambda_R}{p_{RB}}.$$

For brevity we also use $\rho_A \triangleq \rho_{AR}$, $\rho_R \triangleq \rho_{RA}$, $\tau_A \triangleq \tau_{AR}$, and $\tau_R \triangleq \tau_{RA}$ in what follows.

IV. Mean Delay Estimation

A. General Statements

Consider the queue at node A. We remind that by definition

$$\rho_A = \Pr\{Q_A \neq 0\}$$

and set

$$\rho_{A0} > \rho_{R0}$$

as an example. We may formulate the following proposition.

Proposition 1. For the queue load coefficient at node A it holds

$$\rho_A \leq \frac{\rho_{A0}}{1 - \rho_{R0}}.$$

Another important proposition may be formulated considering normalization condition for the system generating function or balance equations for respective embedded Markov chain.

Proposition 2. For the queue load coefficients at nodes A and R it holds

$$\rho_A - \rho_R = \rho_{A0} - \rho_{R0}.$$

We leave the proof of the above propositions out of scope of this text due to space limitations. Now, accounting for propositions 1 and 2 we may estimate the remaining queue load coefficient at node R as

$$\rho_R = \rho_A - \rho_{A0} + \rho_{R0} \leq \frac{\rho_{A0}}{1-\rho_{R0}} - \rho_{A0} + \rho_{R0}.$$

The obtained estimations for ρ_A and ρ_R are independent of the service discipline and thus valid for both systems with and without cooperation. Below we first consider the system without cooperation for simplicity. Then we describe how our approach for the mean packet delay estimation may be generalized for the system with cooperation.

B. System without Cooperation

We use Pollazek-Khinchine formula [12] to obtain the average queue length at node A as

$$q_A = \lambda_A \tau_A + \frac{\lambda_A^2 x_A}{2\left(1-\lambda_A \tau_A\right)},$$

where τ_A is the first moment of the service discipline for the packets from A (the mean duration of a service cycle T_A) and x_A is the second moment. Accounting for the fact that $\rho_A = \lambda_A \tau_A$, we obtain

$$q_A = \rho_A + \frac{\lambda_A^2 x_A}{2\left(1-\rho_A\right)}.$$

Consider a service cycle at node A that starts when a packet is ready for service and ends when its service is over. We remind that the scheduler at the base station is stochastic and selects the node A with probability 0.5 if both are loaded. Therefore, in each slot where $Q_A \neq 0$ and $Q_R \neq 0$ the packet from the node A is scheduled with probability 0.5 and an auxiliary probability is

$$p \triangleq \Pr\left\{Q_R \neq 0 | Q_A \neq 0\right\} = \frac{\Pr\left\{Q_R \neq 0, Q_A \neq 0\right\}}{\Pr\left\{Q_A \neq 0\right\}}.$$

As such, we assume that the scheduler assigns a slot to the node R with probability $\frac{1}{2}p$ and assigns a slot to the node A with probability $1-\frac{1}{2}p$. From the above it follows

$$\frac{p}{2} = \frac{\rho_A - \rho_{A0}}{\rho_A}.$$

Let the service for a packet from node A conditioning on the fact that the queue at the node R is empty takes exactly i slots. The possible system events are given in Table 1.

Summarizing, the service discipline may be formulated as

$$\Pr\left\{T_A = n\right\} = p_{AB}\left(1-\frac{p}{2}\right)\left(1-p_{AB}+p_{AB}\frac{p}{2}\right)^{n-1}.$$

Using the above expression, the second moment of the service discipline may be established as

$$x_A = \frac{2-p_{AB}+p_{AB}\frac{p}{2}}{p_{AB}^2\left(1-\frac{p}{2}\right)^2},$$

and we also remind that the mean duration of the service cycle (the first moment of the service discipline) is $\tau_A = \frac{\rho_A}{\lambda_A}$.

Therefore, the resulting expression for the mean packet delay of node A may be obtained as

$$\delta_A = \frac{\rho_A}{\lambda_A} + \frac{\lambda_A\left(2-p_{AB}+p_{AB}\frac{p}{2}\right)}{2\left(1-\rho_A\right)p_{AB}^2\left(1-\frac{p}{2}\right)^2}.$$

The characteristics of the node R are obtained similarly since the channels are symmetric. The mean duration of the service cycle is $\tau_R = \frac{\rho_R}{\lambda_R}$ and

$$\frac{p'}{2} = \frac{\rho_R - \rho_{R0}}{\rho_R}.$$

Finally, the mean packet delay of node R is

$$\delta_R = \frac{\rho_R}{\lambda_R} + \frac{\lambda_R\left(2-p_{RB}+p_{RB}\frac{p'}{2}\right)}{2\left(1-\rho_R\right)p_{RB}^2\left(1-\frac{p'}{2}\right)^2}.$$

C. System with Cooperation

In order to describe the system with cooperation we firstly consider an important special case when the queue at node R is always empty. We thus aim at obtaining the distribution of the number of slots necessary to serve a packet from the node A. We then use the established distribution to generalize the above approach for the system without cooperation. All the respective characteristics for the system with cooperation are marked with superscript $*$ sign below.

Case I. Queue at node R is always empty ($\lambda_R = 0$).

Several important events that simplify the derivation of the sought service discipline are given in Table 2.

Summarizing, the service discipline may be formulated as

$$\begin{aligned}
&\Pr\left\{T_{A0}^* = i\right\} = \\
&\quad = p_{AR} \cdot p_{CB}\left(1-p_{AB}\right) \cdot \\
&\quad \cdot \frac{\left(1-p_{CB}\right)^{i-1} - \left(1-p_{AB}\right)^{i-1}\left(1-p_{AR}\right)^{i-1}}{\left(1-p_{CB}\right) - \left(1-p_{AB}\right)\left(1-p_{AR}\right)} + \\
&\quad + p_{AB}\left(1-p_{AB}\right)^{i-1}\left(1-p_{AR}\right)^{i-1}.
\end{aligned}$$

For brevity let

$$X = \frac{p_{AR} \cdot p_{CB}\left(1-p_{AB}\right)}{\left(1-p_{CB}\right) - \left(1-p_{AB}\right)\left(1-p_{AR}\right)} \text{ and}$$

$$Y = \frac{p_{AR} \cdot p_{CB}\left(1-p_{AB}\right)}{\left(1-p_{CB}\right) - \left(1-p_{AB}\right)\left(1-p_{AR}\right)} - p_{AB}.$$

Then the expression for the service discipline simplifies to

$$\Pr\left\{T_{A0}^* = i\right\} = X\left(1-p_{CB}\right)^{i-1} - Y\left[\left(1-p_{AB}\right)\left(1-p_{AR}\right)\right]^{i-1}.$$

For the obtained service discipline we may calculate its first moment as

$$\tau_{A0}^* = \frac{p_{CB} + \left(1-p_{AB}\right)p_{AR}}{p_{CB}\left[p_{AB} - \left(1-p_{AB}\right)p_{AR}\right]}.$$

Table 1. Possible events for system without cooperation:

Slots	Probability	Service cycle	Description	Expression
1	p_{AB}	1	1st slot assigned to A	$\left(1-\frac{1}{2}p\right)$
		2	1st slot assigned to R, 2nd slot assigned to A	$\frac{p}{2}\left(1-\frac{1}{2}p\right)$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
		n	n slots assigned to R, $(n+1)$st slot assigned to A	$\left(\frac{p}{2}\right)^n\left(1-\frac{1}{2}p\right)$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
2	$p_{AB}\left(1-p_{AB}\right)$	2	1st slot assigned to A, 2nd slot assigned to A	$\left(1-\frac{1}{2}p\right)^2$
		3	1 slot assigned to R before A (2 options)	$2\left(\frac{p}{2}\right)\left(1-\frac{1}{2}p\right)^2$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
i	$p_{AB}\left(1-p_{AB}\right)^{i-1}$	i	no slots assigned to R, just to A	$\left(1-\frac{1}{2}p\right)^i$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
		$i+(n-i)=n$	i slots to A and $(n-i)$ slots to R, possible combinations	$\left(\frac{p}{2}\right)^{n-i}\left(1-\frac{1}{2}p\right)^i\cdot\begin{pmatrix} n-1 \\ n-i \end{pmatrix}$

Table 2. Important events for system with cooperation:

Event	Probability	Description
P_1	p_{AB}	Packet served immediately
P_2	$\left(1-p_{AB}\right)p_{AR}p_{CB}$	R helps after 1st slot
	$\left(1-p_{AB}\right)\left(1-p_{AR}\right)p_{AB}$	R never helps
$\cdots$	$\cdots$	$\cdots$
P_{i+1}	$\left(1-p_{AB}\right)p_{AR}\left(1-p_{CB}\right)^{i-1}p_{CB}$	R helps after 1st slot
	$\left(1-p_{AB}\right)\left(1-p_{AR}\right)^{j-1}p_{CB}\left(1-p_{CB}\right)^{i-1-(j-1)}p_{AR}$	R helps after jth slot
	$\left(1-p_{AB}\right)^i\left(1-p_{AR}\right)^2 p_{AB}$	R never helps
$\cdots$	$\cdots$	$\cdots$

The established expression for $\Pr\left\{T_{A0}^*=i\right\}$ may be used analogously to the above system without cooperation. Compare the form

$$\Pr\left\{T_{A0}=i\right\}=p_{AB}\left(1-p_{AB}\right)^{i-1}$$

for the system without cooperation (see Table 1) and the above form $\Pr\left\{T_{A0}^*=i\right\}$ for the system with cooperation.

Case II. Queue at node R is not always empty ($\lambda_R>0$).

We generalize the above approach for the most complicated cooperative case with $\lambda_R>0$. Omitting complex, but straightforward derivations, we establish

$$\begin{aligned}\Pr\left\{T_A^*=n\right\}&= \\ &=X\left(1-\frac{p^*}{2}\right)\left(1-p_{CB}+p_{CB}\frac{p^*}{2}\right)^{n-1}- \\ &-Y\left(1-\frac{p^*}{2}\right)\left(1-p_A+p_A\frac{p^*}{2}\right)^{n-1},\end{aligned}$$

where

$$\frac{p^*}{2}=\frac{\rho_A^*-\rho_{A0}^*}{\rho_A^*}$$

and for brevity

$$p_A=p_{AB}+p_{AR}-p_{AB}\cdot p_{AR}.$$

The queue load coefficients at nodes A and R (ρ_A^* and ρ_R^*) may be calculated similarly to those in the system without cooperation, accounting for the fact that

$$\rho_{A0}^*\triangleq\lambda_A\tau_{A0}^*,$$

where τ_{A0}^* was established previously.

Finally, we calculate the second moment of the obtained service discipline as

$$x_A^*=\frac{1}{\left(1-\frac{p^*}{2}\right)^2}\left(X\cdot\frac{2-p_{CB}+p_{CB}\frac{p^*}{2}}{p_{CB}^3}-Y\cdot\frac{2-p_A+p_A\frac{p^*}{2}}{p_A^3}\right)$$

and establish

$$\begin{aligned}\delta_A^*&= \\ &=\frac{\rho_A^*}{\lambda_A}+\frac{\lambda_A}{2\left(1-\rho_A^*\right)\left(1-\frac{p^*}{2}\right)^2}\cdot \\ &\cdot\left(X\cdot\frac{2-p_{CB}+p_{CB}\frac{p^*}{2}}{p_{CB}^3}-Y\cdot\frac{2-p_A+p_A\frac{p^*}{2}}{p_A^3}\right),\end{aligned}$$

where X and Y are given above.

The resulting characteristics for the node R in the system with cooperation are similar to those for the node R in the system without cooperation and were calculated previously.

V. Numerical Results

Below we verify the obtained analytical estimation of mean packet delay for both the originator and the relay by the means of simulation. We use our own simulator that tracts down the main features of contemporary IEEE 802.16-2009 WiMAX specification. IEEE 802.16 MAC layer adopts a schedule-based protocol, commonly operating in the mandatory centralized mode, which is naturally suitable for the basic client relay model verification.

The base station arbitrates all activity within the network and broadcasts both service messages and data packets to its clients in the *downlink* (DL) sub-frame. The DL sub-frame is composed of a 802.16 MAC header and DL bursts, directed at the clients. In the *uplink* (UL) sub-frame the clients transmit scheduled UL bursts as well as service messages. We assume that there are only two clients, the originator and the relay and the base station has no DL traffic. The exact IEEE 802.16-2009 timings are given in Figure 3.

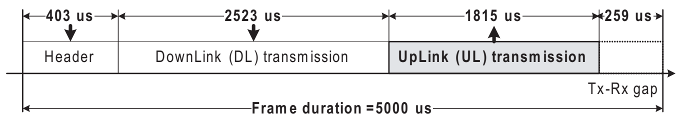

Figure 3. Exact IEEE 802.16 OFDMA frame timings

IEEE 802.16 supports several PHY layer modes, of which the most practical is the *orthogonal frequency division multiple access* (OFDMA) scheme. In order to bring the simulator closer to the simplified client relay model under consideration we control PHY data rate such that the packet transmission takes exactly one OFDMA uplink sub-frame. For convenience, we express the mean arrival rate in packets per frame. Additionally, we borrow the individual link transmission probabilities of the error-prone MPR channel model from [18]. To ensure the sufficient precision of the obtained simulation results each simulation run lasts $4\ 000$ real-time hours. The most important simulation parameters are summarized in Table 3.

Table 3. Main simulation parameters:

Parameter	Value
Protocol version	IEEE 802.16-2009
DL:UL ratio	60:40
PHY type	OFDMA
Frame duration	5 ms
p_{AB}	0.3
p_{RB}	0.7
p_{AR}	0.4
p_{CB}	0.5
Simulation run duration	4 000 hours

The results of verification are presented in Figure 4. We concentrate on two scenarios with fixed relay mean arrival rate λ_R equal to 0.15 and 0.20 packets per frame (see left and right parts of Figure 4, respectively). Then we increase originator mean arrival rate λ_A and investigate the mean packet delay for both the originator and the relay, as well as their mean departure rates. The delay plots (see bottom of Figure 4) are given in logarithmic scale for convenience.

Firstly, we notice that the established analytical mean delay estimation shows extremely good accordance with simulation results for both scenarios even if the originator queue approaches saturation (shown by a vertical asymptote). Clearly, originator saturation threshold is lower for the second scenario with $\lambda_R = 0.2$ (see right part of Figure 4) as there are on average more packets from node R in the system. Notice that despite the fact that relay mean arrival rate is constant, its mean packet delay grows with increasing λ_A as more packets from node A are scheduled by the base station and the packets from node R consequently have to wait longer.

VI. Summary and Conclusions

The proliferation of wireless networks introduces novel important research directions, including client cooperation, energy efficient communication, co-existence, spectrum aggregation techniques and others. These directions are insufficiently addressed by the conventional simulation methodology and existing analytical models, which cover only static or semi-static cellular environments [4]. Moreover, known models fail to account for many realistic performance factors, such as realistic traffic arrival flows, predefined QoS parameters, wireless channel degradation factors, etc.

As the result, the output of these models provides inadequate insight into the performance of a real-world wireless network. The main target of this paper is to make the first step toward the development of the advanced system model that may be used for the performance evaluation of a practical relay-enhanced multi-cell communications system compliant to the latest IEEE 802.16m [1] and/or LTE-Advanced [2] specifications.

Accounting for channel variation across clients via cooperative techniques may be extensively used in joint MAC-PHY design to improve spectral efficiency, energy efficiency, and QoS perception of wireless clients. By exploiting channel state information of different clients, the proposed approach leads to integrated algorithms, which utilize spectrum and energy resources both fairly and efficiently. Existing knowledge on efficiency, QoS, fairness, and stability of channel-aware approaches might benefit from this study. The resulting complex research may result in both theoretical innovations and practical applications, as this topic may lead to rethinking the architecture of contemporary multimedia-over-wireless networks.

The basic client cooperation model evaluated within this study appears to be the first of its kind and indicates significant promise for the entire research area. The obtained analytical results are in the perfect agreement with simulation data. It is expected that the novel model and its extensions will become of significant importance toward further development of wireless communication technologies. It is primarily intended for, but not limited to, cellular operators, telecommunications research companies, cellular equipment vendors and mobile software companies.

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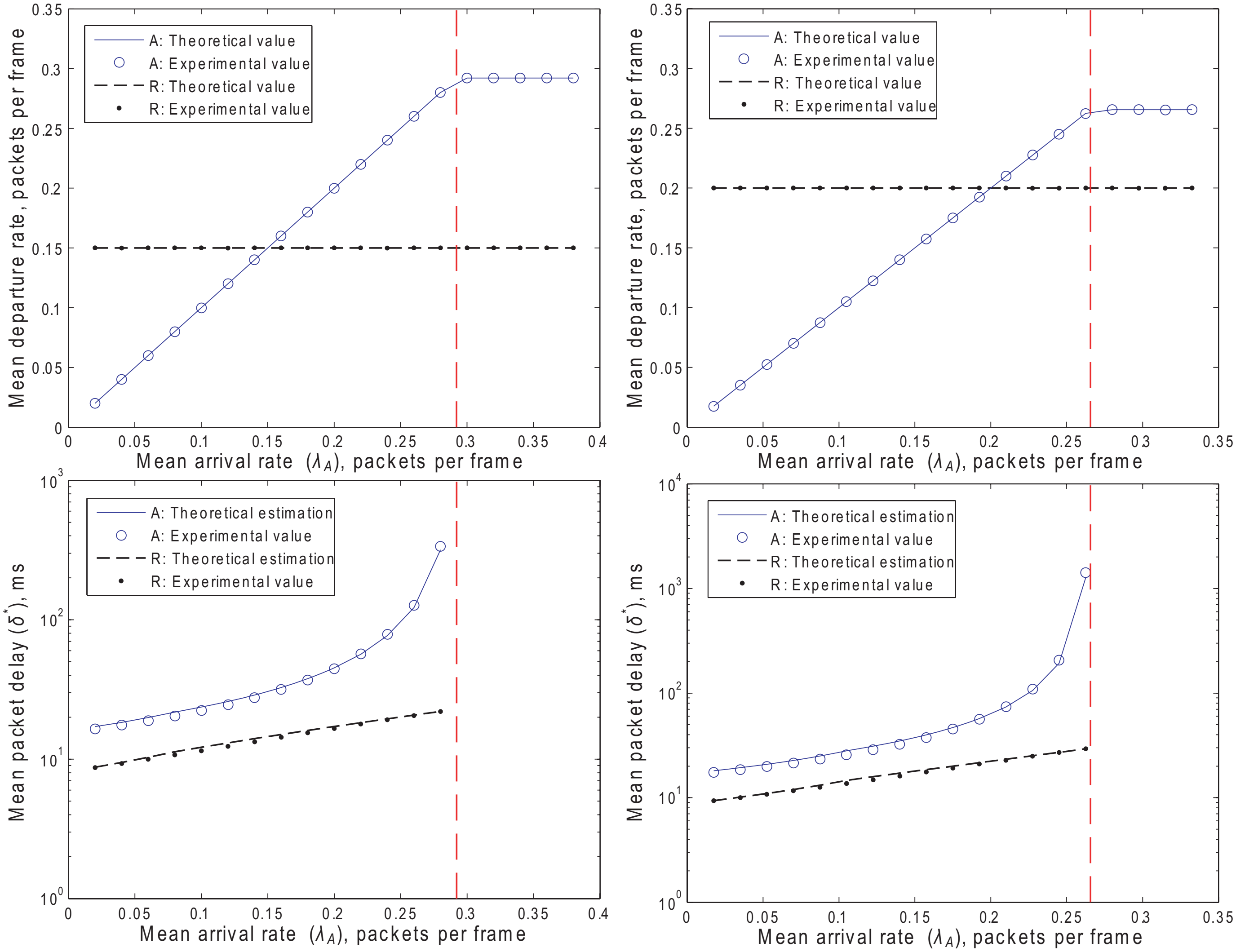

Figure 4. Results verification for two scenarios with $\lambda_R = 0.15$ (left) and $\lambda_R = 0.20$ (right)

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