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## *Aims and Scope*

Optimization has been expanding in all directions at an astonishing rate during the last few decades. New algorithmic and theoretical techniques have been developed, the diffusion into other disciplines has proceeded at a rapid pace, and our knowledge of all aspects of the field has grown even more profound. At the same time, one of the most striking trends in optimization is the constantly increasing emphasis on the interdisciplinary nature of the field. Optimization has been a basic tool in all areas of applied mathematics, engineering, medicine, economics, and other sciences.

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Antonio José Vázquez Álvarez  
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# An Introduction to Optimal Satellite Range Scheduling

 Springer

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*To my parents.*      *A. J.*

*To my wife, my son, and my parents.*      *R. S.*



# Preface

The problem of scheduling interactions among satellites and ground stations has been around for decades, and most of the literature tackling this problem has focused on approximate solutions. In this book we have tried to find the optimal solution to this problem and some of its variants and also to unify criteria and notation across the satellite range scheduling literature. To our knowledge, this is the first work that will accomplish both objectives.

We wrote this book as a result of a 2-year (2013–2015) postdoctoral fellowship at the Air Force Research Laboratory, funded by the National Research Council. The major results contained herein were published as a series of conference and journal papers during this period. This work, although based on these publications, considerably extends them by solving new problems and binding them together as a whole.

This endeavor has not been easy, with telecommunication and control engineering backgrounds for tackling a problem from operations research. We think however that this combination provides increased value to this book, and we have in fact tried to make it accessible to those readers that are facing this problem for the first time. This book is also aimed at satellite operations engineers and scheduling algorithm designers, as we here provide reference (optimal) solutions to this problem and some of its most important variants.

We are conscious that we are only scratching the surface on satellite range scheduling, but we have tried to provide a strong framework over which keep finding solutions to more complex problems in this field. We hope this book keeps up with the high standards of previous literature in this field, and more importantly, we hope this book to be useful to students and algorithm designers.

Albuquerque, NM, USA  
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April 2015

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I would like to thank Springer for their trust in this project since its inception and for providing the L<sup>A</sup>T<sub>E</sub>X monograph template. Finally I would like to thank Springer, Scitepress, and IEEE for granting us permission for recasting some materials from our previous work. We have generated all the diagrams with DIA and Inkscape and the simulation maps and graphs with MATLAB and did the typesetting in MiKTeX.

A. J.

I would like to thank first my wife, Kim, and my son, Ian; it is the time I have spent away from them, or the times I have been home but not present, that are the real price paid for accomplishments such as this.

---

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I would like to thank my parents, Richard and Barbara, for giving me the opportunities in life that led to the successes I have enjoyed.

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R. S.

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# Acronyms

AFSCN	Air Force Satellite Control Network
DAG	Directed acyclic graph
DSN	Deep Space Network
EOS	Earth observation satellite
ESA	European Space Agency
ESTRACK	ESA Tracking Station Network
FI	Fixed interval
Fig.	Figure
FNE	Fixed number of entities
GB	Gigabyte
GEO	Geostationary Earth orbit
GHz	Gigahertz
GS	General scheduling
LEO	Low Earth orbit
LOS	Line of sight
MuRRSP	Multiple resource range scheduling problem
N/A	Not applicable
NASA	National Aeronautics and Space Administration
NP	Nondeterministic polynomial
P	Polynomial
PoA	Price of anarchy
RAM	Random access memory
SiRRSP	Single resource range scheduling problem
SRS	Satellite Range Scheduling
SW	Social welfare
TVG	Time varying graph





# Symbols

$\alpha$	First term in unified notation
$\alpha_l$	Failure probability for pass $p_l$
$\alpha_{j,m}$	Failure probability for pass $p_{j,m}$ in $P_j^w$ associated to $p_j^w$
$\alpha_{j,k,m}$	Failure probability for pass $p_{j,k,m}$ in $P_{j,k}^w$ associated to $j_j^w$
$\beta$	Second term in unified notation
$\beta_{j,m}$	Probability for the priority value $w_{j,m}$ for the pass $p_j^w$
$\beta'_{j,m}$	Probability for the duration value $\rho_{j,m}$ for the request $j_j^w$
$\beta'_{j,k,m}$	Probability for the pass $p_{j,k,m}$ in $P_{j,k}^w$ associated to $j_j^w$
$\gamma$	Third term in unified notation
$\Gamma_j$	Finite discrete random variable for the durations of the pass $p_j^w$
$\Delta t$	Discretization time step
$\rho_j$	Duration of request $j_j$
$\bar{\rho}_j$	Maximum duration of request $j_j$
$\underline{\rho}_j$	Minimum duration of request $j_j$
$\bar{\bar{\rho}}$	Maximum duration among all requests
$\tau_c$	Minimum time between priority changes
$\tau_{e_j}$	End time of visibility window $o_j$
$\tau_{s_j}$	Start time of visibility window $o_j$
$\phi$	Sign of event
$\phi(p_m, p_l)$	Function for checking conflict between passes $p_l$ and $p_m$
$\phi_g(p_k)$	Ground station associated to pass $p_k$
$\phi_s(p_k)$	Satellite associated to pass $p_k$
$\psi_l$	Sub-tree associated to node $n_l$ in extensive form representation
$\omega_a$	Payoff reduction constant for unfeasible paths
$a_k$	Priority normalization factor
$a_{p_l}$	Action performed for pass $p_l$
$A_b$	Algorithm for generating the backward graph
$A_f$	Algorithm for generating the forward graph
$A_i(l)$	Nodes added to the frontier $B_i$ for node $n_l$

$A_i$	Set of actions for satellite $s_i$
$A_p$	Algorithm for finding best pairs in the overlaid graphs $G_f$ and $G_b$
$A_r$	Algorithm for finding the alternative longest paths
$b$	Edge in backward graph
$B_i$	Frontier in the graph
$C_\Sigma$	Unitary capacity (unified notation)
$C_\Sigma(P')$	Total number of conflicts for the schedule $P'$
$C_G(P')$	Number of ground station conflicts for the schedule $P'$
$C_S(P')$	Number of satellite conflicts for the schedule $P'$
$C_x$	$m$ -ary capacity (unified notation)
$d$	Number of passes per day
$d_j$	Due time of request $j_j$
$\vartheta_j$	Due time of job $\mathfrak{J}_j$ (unified notation)
$\mathfrak{D}$	Multiple unrelated machines, distributed scheduler (unified notation)
$\mathcal{D}$	Dismissing pass action
$D_i(l)$	Nodes deleted from the frontier $B_i$ for node $n_l$
$D_l$	Set of later nonconflicting passes for $p_l$
$D_n$	Transformation of requests into passes
$e, e^-, e^+$	Event, end time event, and start time event
$E, E^-, E^+$	Set of events, set of end time events, and set of start time events
$f_j^w(t)$	Priority function for request $j_j$
$f_e^-(p_l)$	Function for generating end time event from pass $p_l$
$f_e^+(p_l)$	Function for generating start time event from pass $p_l$
$g_i$	Ground station $i$
$G$	Set of ground stations
$G_b$	Backward graph
$G_f$	Forward graph
$H_l$	History of play until pass $p_l$
$H_{i,l}^s$	History of play for satellite $s_i$ until pass $p_l$
$I_i(l)$	Information available to player $i$ at stage $l$
$I_{PI}$	Perfect information
$I_{UP}$	Uncertain passes information
$I_{UW}$	Uncertain priorities information
$j_j$	Request $j$
$j(e_i)$	Request associated to pass associated to event $e_i$
$J$	Set of requests
$J_{FS}$	Set of requests with fixed slack
$\mathfrak{J}_i$	Job $i$ (unified notation)
$J_i(P')$	Payoff for satellite $s_i$ and schedule $P'$
$J_j^a$	Set of requests that are active for node $n_j$
$J_{NS}$	Set of requests with no slack
$J_{VS}$	Set of requests with variable slack
$J^w$	Set of requests with random durations

$J(n_j)$	Set of requests associated to backtracking from $n_j$ to $n_0$
$k_1$	Number of scheduling resources
$k_2$	Number of scheduling entities
$L$	Longest path in graph before the priority change
$L'$	Longest path in graph after the priority change
$L(n_j)$	Longest path that includes node $n_j$
$L_b(n_y, n_z)$	Longest path in $G_b$ from node $n_y$ to $n_z$
$L_f(n_x, n_y)$	Longest path in $G_f$ from node $n_x$ to $n_y$
$m_j$	Subpath in the graph associated to node $n_j$
$M$	Maximum number of possible priorities (durations) for passes with random priorities (durations)
$M_c$	Maximum number of passes that change priority at the same time
$\mathfrak{M}_i$	Machine (unified notation)
$M_j$	Number of possible priorities (durations) for pass $p_j^w$ (request $j_j^w$ )
$n_{d_j}$	Discrete due time of request $j_j$
$n_{e_k}$	Discrete end time of pass $p_k$
$n_i$	Node in the graph
$n_{r_j}$	Discrete release time of request $j_j$
$n_{s_k}$	Discrete start time of pass $p_k$
$n^*(i, k)$	Best node in $Z_i$ for current stage $Z_k$ with associated pass tracked
$n^0(i, k)$	Best node in $Z_i$ for current stage $Z_k$ with associated pass not tracked
$N$	Number of requests or passes
$o_j$	Visibility window $j$
$O(\cdot)$	Big O notation
$p_{ij}$	Processing time of job $\mathfrak{J}_j$ in machine $\mathfrak{M}_i$ (unified notation)
$p_{ij}^{\text{var}}$	Variable processing time for job $\mathfrak{J}_j$ in machine $\mathfrak{M}_i$ (unified notation)
$\overline{p}_j$	Maximum processing time of job $\mathfrak{J}_j$ (unified notation)
$\underline{p}_j$	Minimum processing time of job $\mathfrak{J}_j$ (unified notation)
$p_{j,m}$	Pass with associated failure probability $\alpha_{j,m}$ generated from $p_j^w$
$p_j^w$	Pass with random priorities
$p_k$	Pass $k$
$p(e_i)$	Pass associated to event $e_i$
$\mathfrak{P}$	Multiple related machines (unified notation)
$P$	Initial set of passes
$P', P'', P_{\text{sub}}$	Schedule
$\tilde{P}$	Executed schedule
$P^*$	Optimal schedule
$P^*(t)$	Updated optimal schedule
$P_j^a$	Set of passes that are active for node $n_j$
$P^d$	Set of passes generated from the set of requests with random durations
$P^{\text{dR}}$	Robust schedule for the robust SRS problem with random durations
$P^f$	Feasible schedule
$P_j^j$	Set of passes generated from request $j_j$

$P_j^w$	Set of passes with failure probabilities generated from $p_j^w$
$P_l$	Set of later passes for $p_l$ , including $p_l$
$P_l^p$	Precedence subset
$P_{nw}$	Set of passes with uncertain priorities
$P^R$	Robust schedule for the robust SRS problem with failure probabilities
$P_i^s$	Subset of $P$ in which passes are associated to $s_i$
$P_i^{sm}$	Security schedule for $s_i$
$P^w$	Initial set of passes with random priorities
$P^{wR}$	Robust schedule for the robust SRS problem with random priorities
$P(n_j)$	Set of passes associated to backtracking from $n_j$ to $n_0$
$P(t)$	Set of passes with time-dependent priorities at time $t$
$P(t) _{t_1}^{t_2}$	Subset of $P(t)$ , which passes have start times in the interval $[t_1, t_2]$
$\mathbb{P}(\cdot)$	Probability
$\bar{q}$	Maximum duration of all visibility windows in discretization
$\underline{q}_j$	Duration of visibility window of discretized request $j$
$\overline{q}_{jk}$	Maximum duration of pass $p_k$ associated to discretized request $j$
$\underline{q}_{jk}$	Minimum duration of pass $p_k$ associated to discretized request $j$
$r_j$	Release time of request $j$
$\mathbf{r}_j$	Release time of job $\mathfrak{J}_j$ (unified notation)
$\mathfrak{R}$	Multiple unrelated machines (unified notation)
$R_i(k)$	Best pair of nodes in $Z_i$ , computed from current stage $Z_k$
$s_h$	Satellite $h$
$s_{\text{lead}}$	Leader satellite
$S$	Set of satellites
$\S$	Section
$t$	Time
$t_0$	Initial time
$t_{e_k}$	End time of pass $p_k$
$t_{s_k}$	Start time of pass $p_k$
$\mathcal{T}$	Tracking pass action
$T$	Duration of the scheduling horizon
$T_g$	Reduced time for the game development
$\mathcal{L}_j$	Lateness of job $\mathfrak{J}_j$ (unified notation)
$U[1, 10]$	Discrete uniform distribution with values between 1 and 10
$v$	Edge in (forward) graph
$\mathbf{w}_j$	Priority of job $\mathfrak{J}_j$ (unified notation)
$w_{j,m}$	Priority of pass $p_{j,m}^w$
$w_k$	Priority of pass $p_k$
$w_{\text{th}}^k(p_z)$	Threshold value for the priority of pass $p_z$ for current stage $Z_k$
w.p.	With probability
$W_i(k)$	Priorities associated to the best pair of nodes $R_i(k)$
$W_j$	Distribution of priorities for $p_j^w$

$Z^+$	Stages associated to start time events in graph
$Z_0$	Initial stage in graph
$\  \cdot \ _{\Sigma w}$	Metric of schedule, e.g., $\ P'\ _{\Sigma w}$
$\  \cdot \ _{\mathbb{E}}$	Expected metric of schedule, e.g., $\ P'\ _{\mathbb{E}}$
$\langle \cdot \rangle_{t_s}$	Set of passes sorted by start time, e.g., $\langle P' \rangle_{t_s}$
$\hat{\cdot}$	Reduced information (unified notation), e.g., $\hat{w}_j, \hat{U}_j$
$\tilde{\cdot}$	Uncertainty (unified notation), e.g., $\tilde{p}_{ij}, \tilde{U}_j$



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