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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 — Antonio José Vázquez Álvarez
Kirtland AFB, NM, USA — Richard Scott Erwin
April 2015

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I would like to thank my parents, Anun and Javier, for all their encouragement, not only during this period but throughout all my life. This work would not be possible without them, which always have been and will be my example. I want to thank my brother Luis too for his encouragement and support in the distance. Very especially I would like to thank my fiancée Nelmy Jerez, meeting her has truly changed my life, and her encouragement and love motivated me to continue with this endeavor.

I would like to thank my research advisor R. Scott Erwin, coauthor of this book, for all his help and trust during this period. He has always pointed the research in the right direction if I diverged too much, and since the beginning he has always shared his knowledge and gave me several pieces of valuable advice. I would also like to thank all the people I have met in AFRL, COSMIAC, and UNM, especially Alonzo Vera, Carolin Früh, Craig Kief, David Alexander, Frederick Leve, Moriba Jah, Robert Terselic, and many others who have been very helpful and friendly.

I am very grateful to the National Research Council[1] for this opportunity and for all their support during this period, especially to Peggy Wilson, who has always answered my never-ending lists of questions.

I would like to thank Springer for their trust in this project since its inception and for providing the LaTeX 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.

[1]This research was performed while the author held a National Research Council Research Associateship Award at the Air Force Research Laboratory (AFRL).

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.

Finally, I'd like to thank my coauthor, Antonio, for his incredible efforts producing the results herein as well as in preparing this monograph.

R. S.

Contents

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

α	First term in unified notation
α_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 $P_{j,k}^{\mathrm{w}}$ associated to $\mathrm{j}_j^{\mathrm{w}}$
β	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 $\mathrm{j}_j^{\mathrm{w}}$
$\beta'_{j,k,m}$	Probability for the pass $p_{j,k,m}$ in $P_{j,k}^{\mathrm{w}}$ associated to $\mathrm{j}_j^{\mathrm{w}}$
γ	Third term in unified notation
Γ_j	Finite discrete random variable for the durations of the pass p_j^{w}
Δt	Discretization time step
ρ_j	Duration of request j_j
$\overline{\rho_j}$	Maximum duration of request j_j
$\underline{\rho_j}$	Minimum duration of request j_j
$\overline{\overline{\rho}}$	Maximum duration among all requests
τ_{c}	Minimum time between priority changes
τ_{e_j}	End time of visibility window o_j
τ_{s_j}	Start time of visibility window o_j
ϕ	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
ψ_l	Sub-tree associated to node n_l in extensive form representation
ω_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

$\mathbf{A}_i$	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_Σ	Unitary capacity (unified notation)
$C_\Sigma(P')$	Total number of conflicts for the schedule P'
$C_{\mathrm{G}}(P')$	Number of ground station conflicts for the schedule P'
$C_{\mathrm{S}}(P')$	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
$\mathfrak{d}_{\mathrm{j}}$	Due time of job $\mathfrak{J}_{\mathrm{j}}$ (unified notation)
$\mathfrak{D}$	Multiple unrelated machines, distributed scheduler (unified notation)
$\mathscr{D}$	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
$f_j^{\mathrm{w}}(t)$	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
$H_{i,l}^{\mathrm{s}}$	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
$\mathrm{j}(e_i)$	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
$L_{\mathrm{b}}(n_y, n_z)$	Longest path in G_{b} from node n_y to n_z
$L_{\mathrm{f}}(n_x, n_y)$	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 $\mathrm{j}_j^{\mathrm{w}}$)
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
$\mathfrak{p}_{ij}$	Processing time of job $\mathfrak{J}_j$ in machine $\mathfrak{M}_i$ (unified notation)
$\mathfrak{p}_{ij}^{\mathrm{var}}$	Variable processing time for job $\mathfrak{J}_j$ in machine $\mathfrak{M}_i$ (unified notation)
$\overline{\mathfrak{p}_j}$	Maximum processing time of job $\mathfrak{J}_j$ (unified notation)
$\underline{\mathfrak{p}_j}$	Minimum processing time of job $\mathfrak{J}_j$ (unified notation)
$\overline{p_{j,m}}$	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
$P', P'', P_{\mathrm{sub}}$	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^{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
$\overline{\overline{q}}$	Maximum duration of all visibility windows in discretization
$\overline{\overline{q_j}}$	Duration of visibility window of discretized request j_j
$\overline{q_{jk}}$	Maximum duration of pass p_k associated to discretized request j_j
$\underline{q_{jk}}$	Minimum duration of pass p_k associated to discretized request j_j
r_j	Release time of request j_j
$\mathfrak{r}_j$	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_{lead}	Leader satellite
S	Set of satellites
§	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
$\mathscr{T}$	Tracking pass action
T	Duration of the scheduling horizon
T_{g}	Reduced time for the game development
$\mathfrak{U}_j$	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
$\mathfrak{w}_j$	Priority of job $\mathfrak{J}_j$ (unified notation)
$w_{j,m}$	Priority of pass $p_{j,m}^{\mathrm{w}}$
w_k	Priority of pass p_k
$w_{\mathrm{th}}^k(p_z)$	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., $\widehat{\mathfrak{w}}_j$, $\widehat{\mathfrak{U}}_j$
$\tilde{\cdot}$	Uncertainty (unified notation), e.g., $\widetilde{\mathfrak{p}}_{ij}$, $\widetilde{\mathfrak{U}}_j$

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