A PTAS for ΔMRCT

metric

Kun-Mao Chao
@ 2019, 2021

- PTAS: Polynomial Time Approximation Scheme

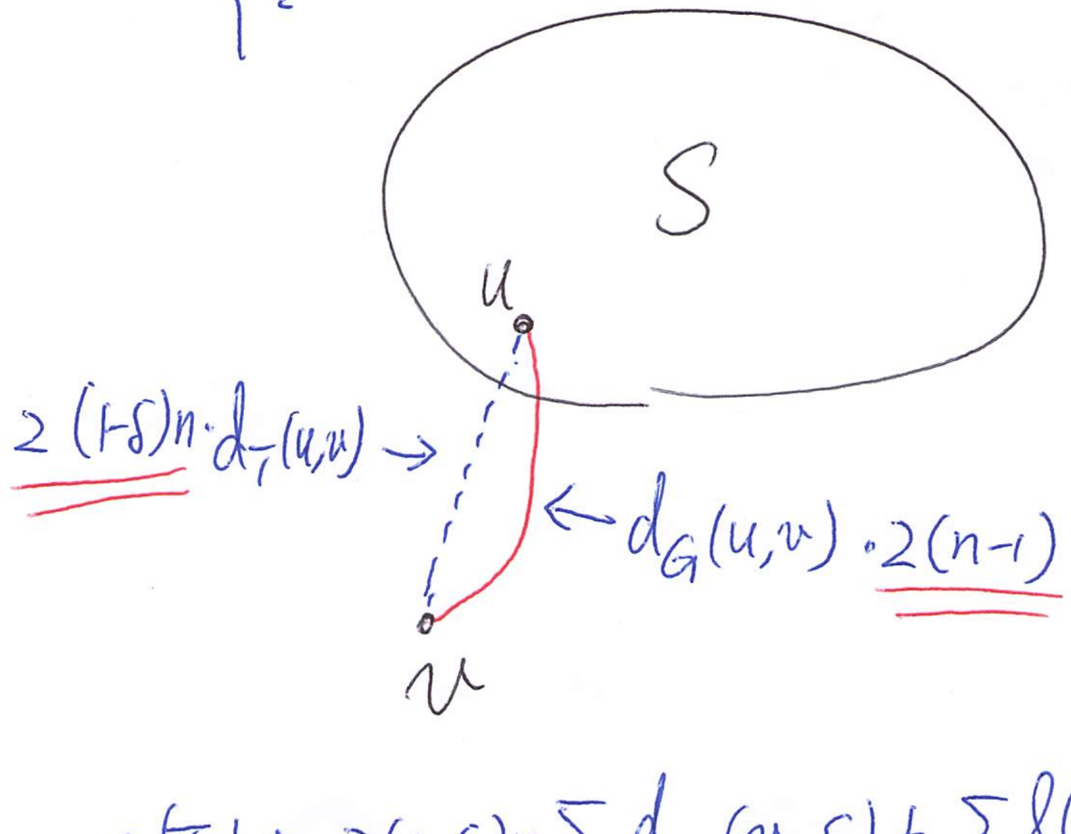
No way!

a. S: a minimal δ-separator of T

b. For each vertex not in S, its lowest ancestor is known.

Y:

$$\frac{C(Y)}{C(T)} \le \frac{1}{1-\delta}$$



$$C(T) \ge 2(1-\delta)n \sum_{v \in V} d_T(v,S) + \sum_{e \in E(S)} \ell(T,e)\, w(e)$$

$$C(Y) = 2(n-1) \sum_{v \in V} d_G(v,S) + \sum_{e \in E(S)} \ell(T,e)\, w(e)$$

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* k-star = a tree with no more than k internal nodes.

δ-spine

* A minimal δ-separator can be cut into several δ-paths ( $\le \frac{1}{2}\delta n$) in a way that the total number of cut nodes and leaves is bounded by $\lceil \frac{2}{\delta} \rceil - 3$.

* There exists a $\left(\lceil \frac{2}{\delta} \rceil - 3\right)$-star Y converted from a tree T satisfying

$$C(Y) \le \left(1 + \frac{\delta}{1-\delta}\right) C(T).$$

* By taking $\delta = \frac{2}{k+3}$, we conclude that an optimal k-star of a metric graph is a $1 + \frac{\frac{2}{k+3}}{1 - \frac{2}{k+3}} = 1 + \frac{\frac{2}{k+3}}{\frac{k+1}{k+3}} = 1 + \frac{2}{k+1} = \frac{k+3}{k+1}$ approximation of an MRCT.

S: a minimal δ-separator

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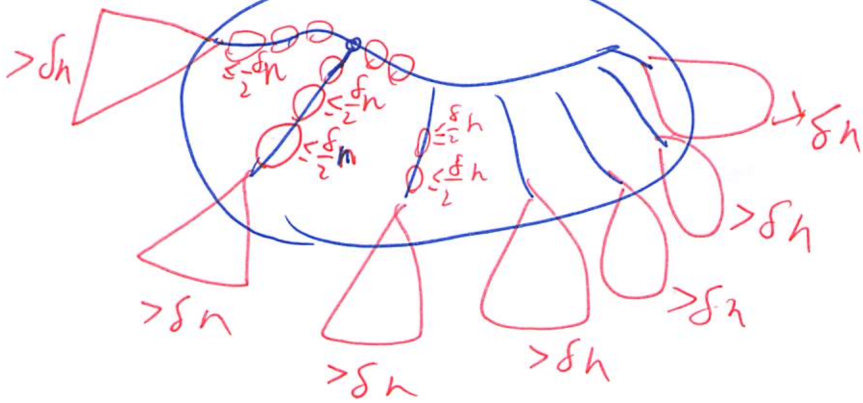


h: # of leaves of S $\quad (\because h(\delta n+1) \le n \Rightarrow h < \frac{1}{\delta})$

h': # of internal nodes of S with degree ≥ 3

$$h' \le h-2 \quad (\because 3h' + h \le 2(h'+h-1))$$

total number of degrees excluding those nodes with degree 2

Notice that a tree with n nodes has n-1 edges, and each edge contributes "two" to the total number of degrees.

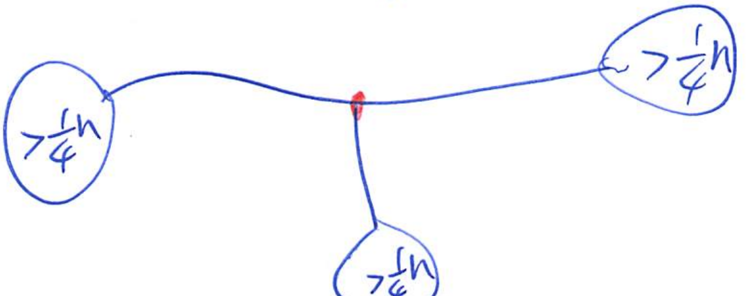
h'': # of additional cutting nodes

$$h'' \le \left\lceil \frac{n-h\delta n}{\frac{\delta n}{2}} \right\rceil - 1 = \left\lceil \frac{2}{\delta} \right\rceil - 2h - 1$$

$$h+h'+h'' \le h+h-2+\left\lceil \frac{2}{\delta} \right\rceil - 2h - 1$$

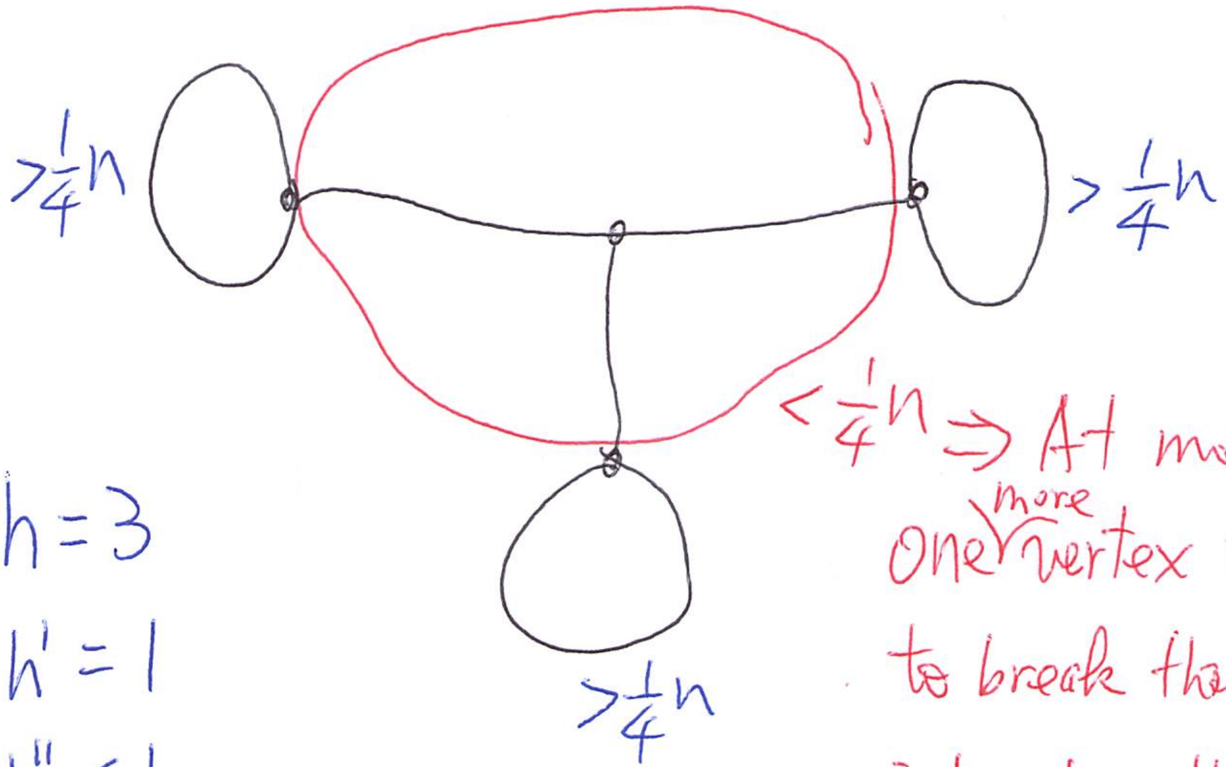
$$= \left\lceil \frac{2}{\delta} \right\rceil - 3$$

a minimal $\frac{1}{4}$-separator



$\left\lceil \frac{2}{8} \right\rceil - 3 = \left\lceil \frac{2}{\frac{1}{4}} \right\rceil - 3 = 5$ Kun-Mao Chao @2019

A minimal $\frac{1}{4}$-separator



$<\frac{1}{4}n \Rightarrow$ At most one more vertex is needed to break the separator into $\frac{1}{4}$-paths, where each $\frac{1}{4}$-path has at most $\frac{1}{8}n$ vertices.

$h = 3$

$h' = 1$

$+)\ h'' \le 1$

≤ 5

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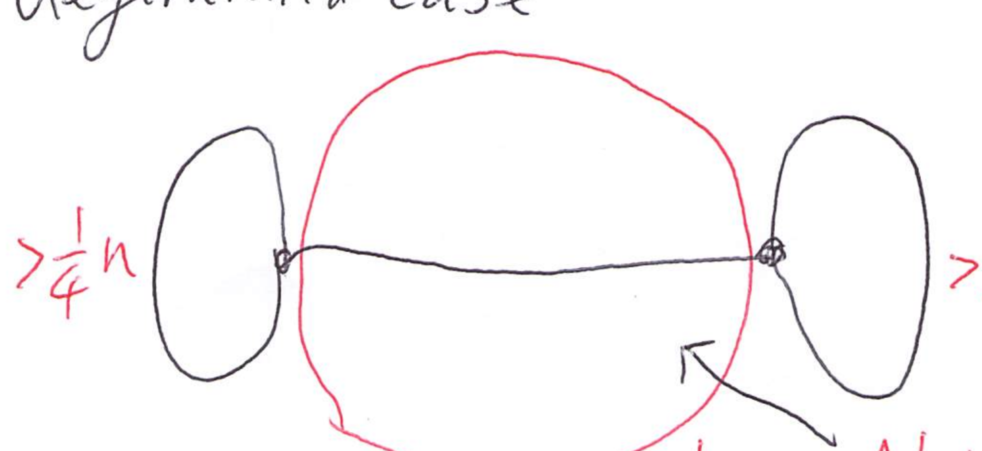
degenerated case



$h = 2$

$h' = 0$

$+)\ h'' \le 3$

≤ 5

$<\frac{1}{2}n \Rightarrow$ At most three more vertices are needed to break the separator into $\frac{1}{4}$-paths.

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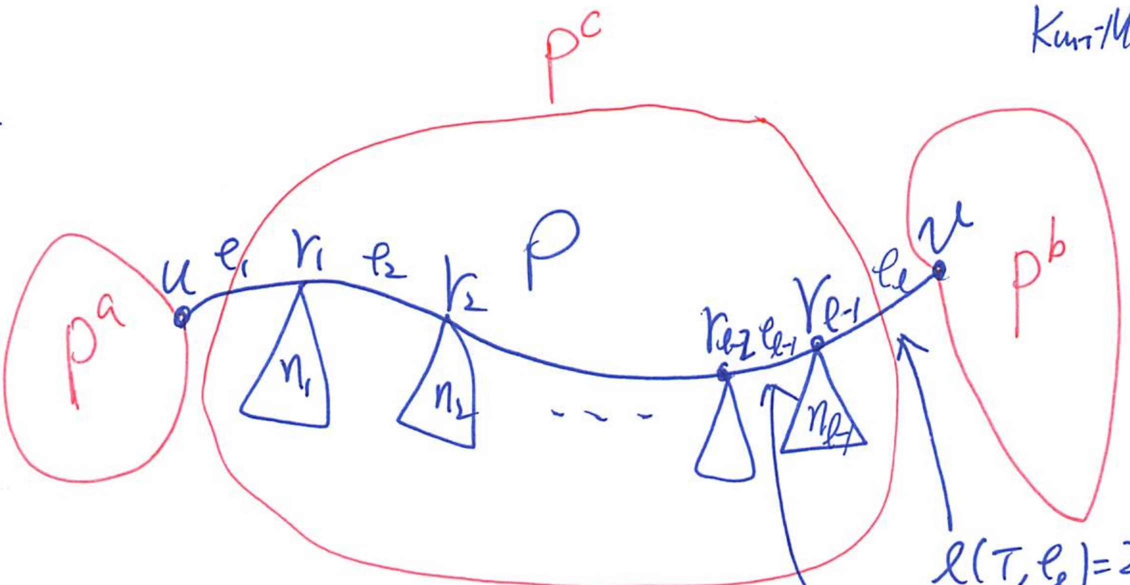
T:



$\ell(T,e_\ell)=2\times(p^a+p^c)\times p^b$

$\ell(T,e_{\ell-1})=2\times(p^a+(p^c-n_{\ell-1}))\times(p^b+n_{\ell-1})$
$=2((p^a+p^c)\times p^b+(p^a-p^b)\cdot n_{\ell-1}+(p^c-n_{\ell-1})\cdot n_{\ell-1})$

Assume that $p^a \geq p^b$

$p^a+p^b+p^c=n$

(i) $$\sum_{e\in P}\ell(T,e)\cdot w(e)=2\sum_{j=1}^{\ell}\Big(p^a+p^c-\sum_{j'=j}^{\ell-1}n_{j'}\Big)\cdot\Big(p^b+\sum_{j'=j}^{\ell-1}n_{j'}\Big)w(e_j)$$

$$=2\Big(\sum_{j=1}^{\ell}(p^a+p^c)\cdot p^b\cdot w(e_j)+(p^a-p^b)\underline{\sum_{j=1}^{\ell}\sum_{j'=j}^{\ell-1}n_{j'}\cdot w(e_j)}+\sum_{j=1}^{\ell}\underbrace{\Big(p^c-\sum_{j'=j}^{\ell-1}n_{j'}\Big)}_{\geq 0}\cdot\underbrace{\sum_{j'=j}^{\ell-1}n_{j'}}_{\geq 0}\cdot\underbrace{w(e_j)}_{\geq 0}\Big)$$

$\sum_{j=1}^{\ell-1}n_j\cdot d_T(u,r_j)$

$n_{\ell-1}(w(e_{\ell-1})+w(e_{\ell-2})+\dots)$
$+n_{\ell-2}(w(e_{\ell-2})+w(e_{\ell-3})+\dots)$
$+\dots$
$+n_1\cdot w(e_1)$

$$\geq 2\Big((p^a+p^c)\cdot p^b\cdot w(P)+(p^a-p^b)\sum_{j=1}^{\ell-1}n_j d_T(u,r_j)\Big)$$

(ii) For $q\in\bigcup_{j=1}^{\ell-1}VB(T,P,r_j)$, $d_T(q,P)$ will be counted at least $2(1-\delta)n$ times.

the routing cost  (X)

$$C(X)\geq 2(1-\delta)n\sum_{q\in \dots}d_T(q,P)+2\Big((p^a+p^c)\cdot p^b\, w(P)+(p^a-p^b)\sum_{j=1}^{\ell-1}n_j d_T(u,r_j)\Big)$$

(ii) (i)

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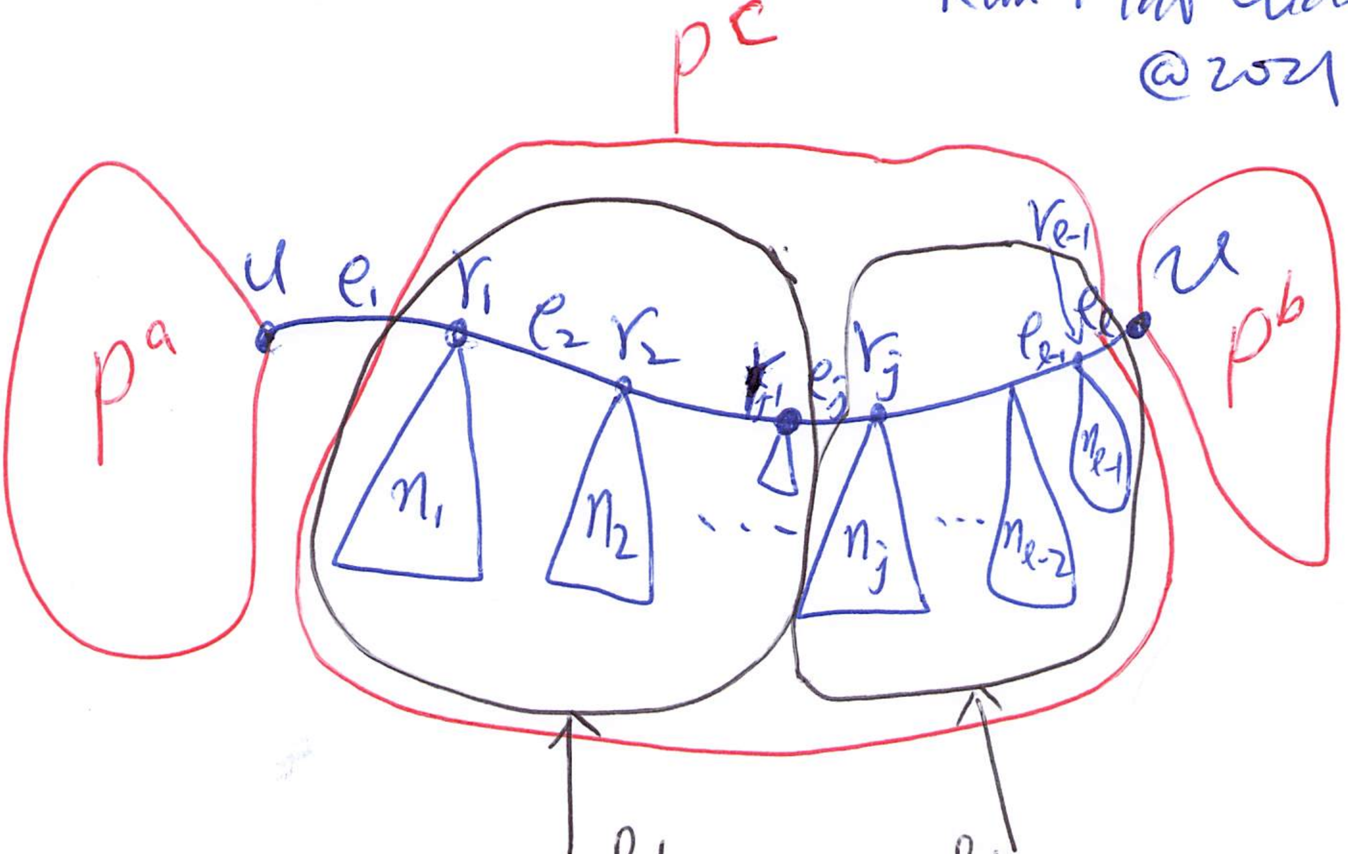

$$p^c - \sum_{j'=j}^{\ell-1} n_{j'} \qquad \sum_{j'=j}^{\ell-1} n_{j'}$$

$$\left(p^a + p^c - \sum_{j'=j}^{\ell-1} n_{j'}\right)\left(p^b + \sum_{j'=j}^{\ell-1} n_{j'}\right)$$

$$= (p^a + p^c)\cdot p^b + (p^a - p^b)\cdot \sum_{j'=j}^{\ell-1} n_{j'} + \underbrace{\left(p^c - \sum_{j'=j}^{\ell-1} n_{j'}\right)}_{\geq 0}\cdot \underbrace{\sum_{j'=j}^{\ell-1} n_{j'}}_{\geq 0}$$

$$\geq (p^a + p^c)\cdot p^b + (p^a - p^b)\cdot \sum_{j'=j}^{\ell-1} n_{j'}$$

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$$\sum_{j=1}^{\ell}\sum_{j'=j}^{\ell-1} n_{j'}\cdot w(e_j)$$

$$=\sum_{j=1}^{\ell-1}\sum_{j'=j}^{\ell-1} n_{j'}\cdot w(e_j)$$

$$= n_{\ell-1}\cdot w(e_{\ell-1}) +$$

$$(n_{\ell-1}+n_{\ell-2})\cdot w(e_{\ell-2}) +$$

$$\cdots +$$

$$(n_{\ell-1}+n_{\ell-2}+\cdots+n_1)\cdot w(e_1)$$

$$= n_{\ell-1}\cdot\big(\underbrace{w(e_{\ell-1})+w(e_{\ell-2})+\cdots+w(e_1)}_{d_T(u,r_{\ell-1})}\big) +$$

$$n_{\ell-2}\cdot\big(\underbrace{w(e_{\ell-2})+\cdots+w(e_1)}_{d_T(u,r_{\ell-2})}\big) +$$

$$\cdots +$$

$$\underbrace{n_1\cdot w(e_1)}_{d_T(u,r_1)}$$

$$= \sum_{j=1}^{\ell-1} n_j\cdot d_T(u,r_j)$$

④-2

X':

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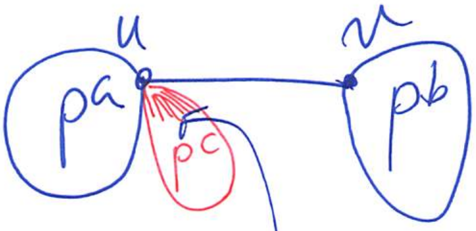
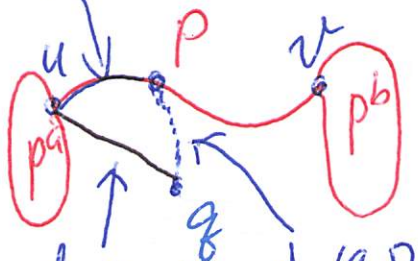


$VB(T, P, r_j) \quad 1 \le j \le l-1$

$d_T(u, r_j) = d_T^P(q, u)$



$q \in VB(T, P, r_j)$

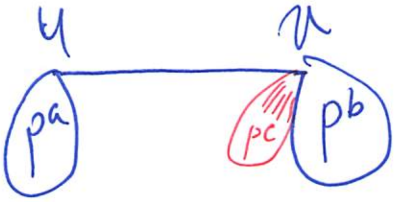
$$d_{X'}(q, u) \le d_T(q, P) + d_T^P(q, u)$$

The routing cost of  (X')

$$\le 2\Big((p^a + p^c)\cdot p^b \cdot \underbrace{w(u,v)}_{\le w(P)} + (n-1)\Big(\sum_{q \in \bigcup_{j=1}^{l-1} VB(T,P,r_j)} d_T(q,P) + \sum_{j=1}^{l-1} n_j \cdot d_T(u, r_j)\Big)\Big)$$

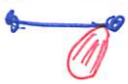
$$\le 2\Big(p^a p^b w(P) + n \sum d_T(q,P) + \boxed{p^b p^c w(P) + n \cdot \sum_{j=1}^{l-1} n_j d_T(u, r_j)}\Big)$$

X'':



$w(P) - d_T(u, r_j) = d_T(r_j, v) = d_T^P(q, v)$

$q \in VB(T, P, r_j),\ 1 \le j \le l-1,\ d_{X''}(q, v) \le d_T(q, P) + d_T^P(q, v)$

The routing cost of  (X'')

$$\le 2\Big((p^b + p^c)\cdot p^a \underbrace{w((u,v))}_{\le w(P)} + (n-1)\Big(\sum_{q \in \bigcup_{j=1}^{l-1} VB(T,P,r_j)} d_T(q,P) + \sum_{j=1}^{l-1} n_j \cdot (w(P) - d_T(u, r_j))\Big)\Big)$$

$$\le 2\Big(p^a p^b w(P) + n \sum d_T(q,P) + \boxed{p^a p^c w(P) + n \cdot \Big(p^c \cdot w(P) - \sum_{j=1}^{l-1} n_j d_T(u, r_j)\Big)}\Big)$$

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$$\boxed{\min\{A,B\} \le \frac{x}{x+y}A + \frac{y}{x+y}B \quad x,y>0}$$

$$\min\{C(X'), C(X'')\}$$

$$\le 2\left(p^a p^b \omega(p) + n\sum d_T(q,p)\right) + \frac{p^a}{p^a+p^b}\cdot\left(p^b p^c \omega(p) + n\sum_{j=1}^{\ell-1} n_j d_T(u,r_j)\right)$$

$$+ \frac{p^b}{p^a+p^b}\left(p^a p^c \omega(p) + n\left(p^c\omega(p) - \sum_{j=1}^{\ell-1} n_j \cdot d_T(u,r_j)\right)\right)$$

$$= 2\left(n\sum d_T(q,p) + \frac{1}{p^a+p^b}\left(p^a\cdot p^b \underbrace{(n-p^c)}_{= p^a+p^b} + 2p^a\cdot p^b\cdot p^c + n p^b p^c\right)\omega(p)\right.$$

$$\left. + \frac{n(p^a-p^b)}{p^a+p^b}\cdot\sum_{j=1}^{\ell-1} n_j\, d_T(u,r_j)\right)$$

※ $\omega(p)$'s coefficient

$$\frac{\min\{C(X'), C(X'')\}}{C(X)} \le \max\left\{\frac{1}{1-\delta}, \frac{\frac{n p^b(p^a+p^c) + p^a p^b p^c}{p^a+p^b}}{(p^a+p^c)p^b}, \frac{\frac{n(p^a-p^b)}{p^a+p^b}}{p^a-p^b}\right\}$$

$$\frac{1}{1-\delta} \ge \frac{1}{1-\frac{1}{2}\delta} = \frac{n}{n-\frac{1}{2}\delta n} \ge \frac{n}{p^a+p^b} =$$

$(\because p^c \le \frac{1}{2}\delta n)$

$$= \max\left\{\frac{1}{1-\delta}, \frac{n}{p^a+p^b} + \frac{p^a\cdot p^c}{(p^a+p^b)(p^a+p^c)}\right\}$$

※ $\omega(p)$'s coefficient

$$\because p^c \le \frac{\delta n}{2} \quad \frac{n}{p^a+p^b} + \frac{p^a\cdot p^c}{(p^a+p^b)(p^a+p^c)} \leftarrow \frac{p^a}{p^a+p^c} \le 1 \qquad = \frac{1}{1-\delta}$$

$$\le \frac{n}{p^a+p^b} + \frac{p^c}{p^a+p^b} = \frac{n+p^c}{p^a+p^b} = \frac{n+p^c}{n-p^c} \le \frac{n+\frac{\delta}{2}n}{n-\frac{\delta}{2}n} = \frac{2+\delta}{2-\delta} = 1+\frac{2\delta}{2-\delta}$$

$$= 1+\frac{\delta}{1-\frac{\delta}{2}} \le 1+\frac{\delta}{1-\delta} = \frac{1}{1-\delta}$$

$\frac{1+x}{1-x}$