value for f_{MS}. Further, the difference (as compared to $ERLA$ and $EXPA$ cases) in f_{MS} widens as η is decreased. Among the correlated arrivals, f_{MS} as a function of η is large initially for MPA (as compared to MNA) and then as η takes a higher value, the roles are reversed; that is, MNA has a larger value for f_{MS} compared to that of MPA. This points to an interesting trend in f_{MS} among correlated arrivals.

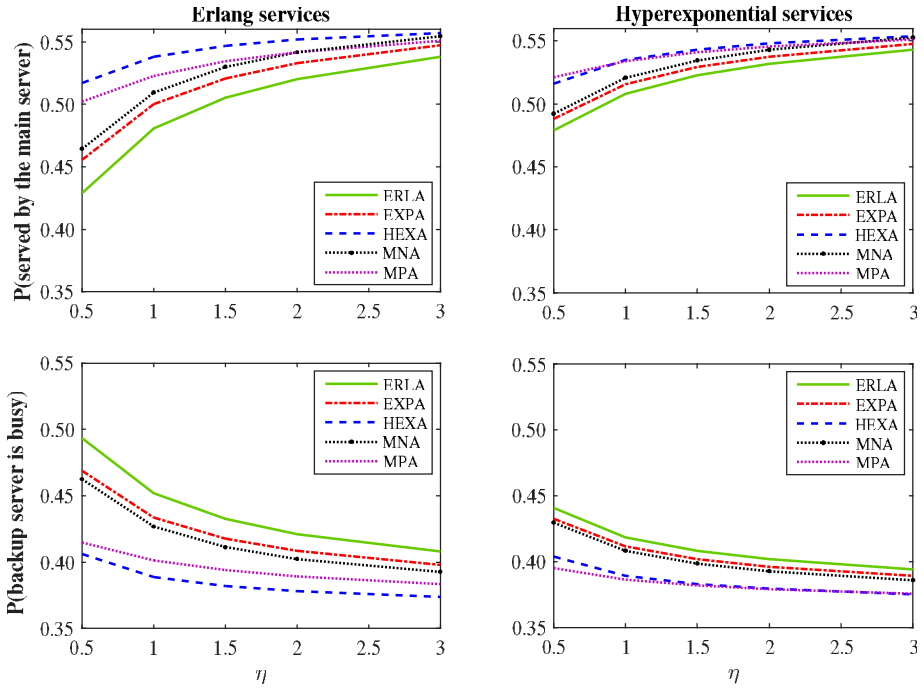

Figure 7.2: Selected performance measures for $ERLS$ and $HEXS$ under different scenarios.

- Also, we observe that $HEXS$ yield a larger value for f_{MS} as compared to $ERLS$.
- The measure, P_{BB}, appears to decrease as a function of η. This is to be expected as an increase in η will decrease the duration of the vacation mode; thus, resulting in a smaller value for this probability.
- A decrease in the variation of the inter-arrival time (or service time) causes P_{BB} to increase. Thus, a decrease in the variation necessitates more usage of the backup server for all values of η.

Example 2: The focus of this example is to look for a minimum value, say ξ^*, of the repair rate, ξ, (when all other parameters are fixed) such that the average numbers in the queue for the model under study (without vacation) and for the classical $MAP/PH/1$ queue do not differ by more than 10^{-3}. Here, by fixing $\lambda = 1.0$, considering two values of $\rho = 0.8, 0.95$, two values for $\gamma = 0.05, 1.0$ and varying θ, ξ^* is displayed in Figs. 7.3 and 7.4 under different scenarios. Note that μ will vary as we vary ρ, ξ, and θ (see (7.89)).

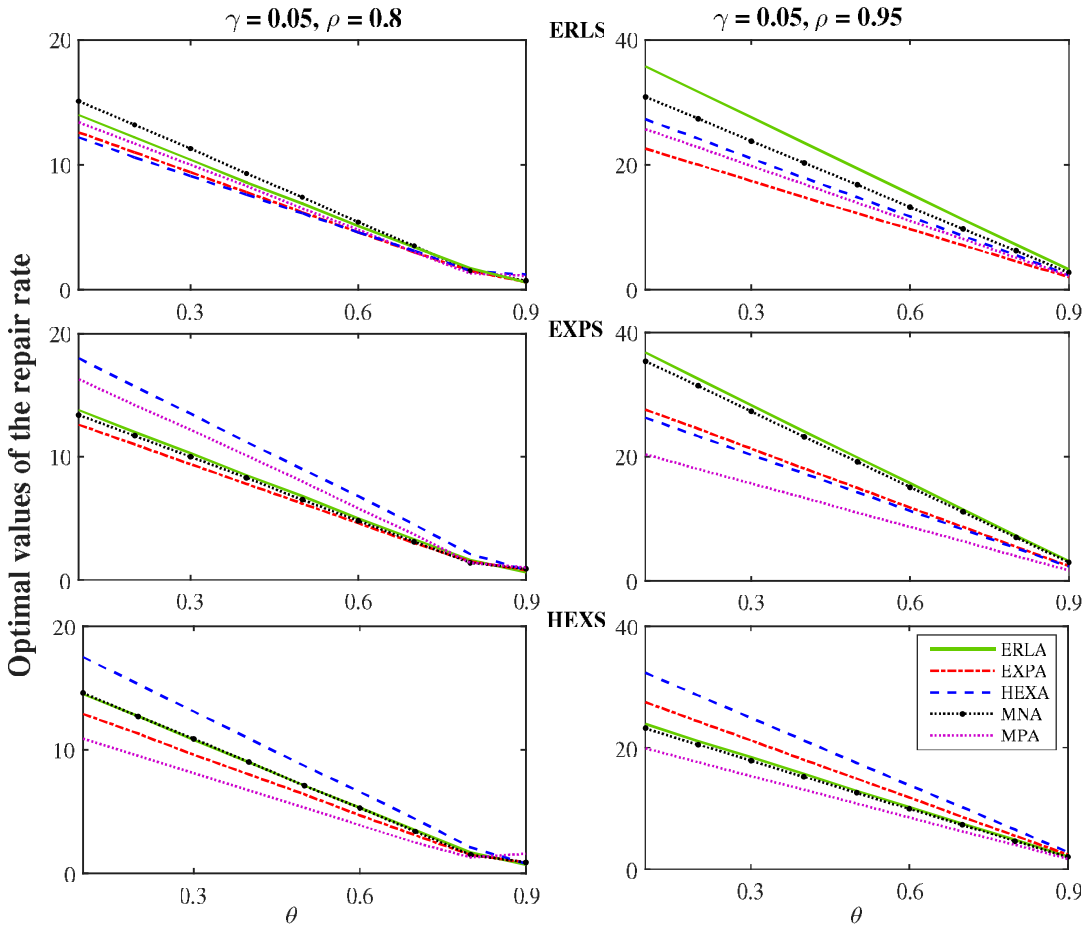

Figure 7.3: Optimal values of the repair rate (ξ) under various scenarios for $\gamma = 0.05$.

Examining the figures reveals the following:

- As θ is increased, ξ^* appears to decrease under all scenarios. Intuitively this happens because of the fact that a higher service rate (of the backup server) requires a

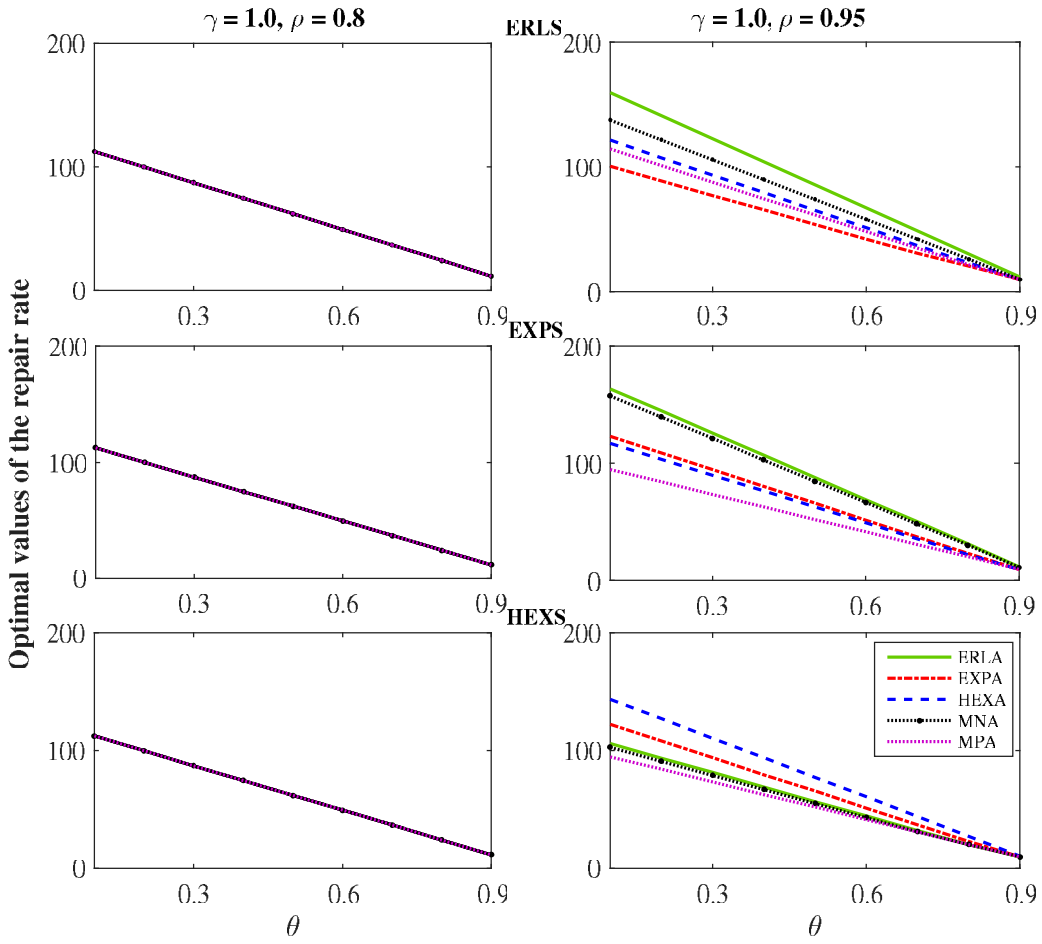

Figure 7.4: Optimal values of the repair rate (ξ) under various scenarios for $\gamma = 1.0$.

lower repair rate to achieve the desired mean number of customers in the queue.

- As ρ increases, a significant increase in the values of ξ^* is observed for all cases considered.

- Among the renewal arrivals, a different pattern is noticed. When $\gamma = 0.05, \rho = 0.8$, for $ERLS$, $ERLA$ produces the largest value whereas for $EXPS$ and $HEXS$, $HEXA$ produces the largest value. However, for $\gamma = 0.05, 1.0$ with $\rho = 0.95$, we observe that for $ERLS$ and $EXPS$, $ERLA$ produces the largest value whereas for $HEXS$, again $HEXA$ produces the largest value.

- It appears that for MNA arrivals, a larger ξ^* is required (under all scenarios con-

sidered except for $EXPS$ with $\rho = 0.8$) as compared to MPA.

- The sensitivity to the type of arrivals and services in the values of ξ^* appears to decrease when θ is increased. This seems to be the case for both values of γ when $\rho = 0.95$.

- Another interesting observation is that for fixed values of θ and ρ, ξ^* increases with an increase in the value of γ for all the arrival and service processes considered.

7.9 Chapter Summary

A queueing model for cellular network, of the type $MAP/PH/1$ in the context of the base station (BS) going on vacations, the BS breaking down due to external shocks, the BS repairs, and the BS being helped by a backup server during vacations and repairs is studied. The proposed model is a generalization to many queueing models and few of them have been discussed as illustrations. This generalization makes the model more suitable for performance evaluation and capacity planning of cellular mobile networks. A qualitative study of the model in steady-state through a number of system performance measures for various scenarios is performed. The decomposition results for the rate matrix and the mean number in the system under some special cases are also proved. Importance of account of correlation, variation in arrival process as well as service process is numerically illustrated.

Chapter 8

Closure

"*Curiosity - the rover and the concept - is what science is all about: the quest to reveal the unknown.*"
— *Ahmed Zewail*

In this chapter, conclusions resulting from the work done in this thesis and contributions towards the operation of cellular networks followed by the directions for future research are presented.

8.1 Conclusions

The thesis addresses two main research questions in cellular mobile networks, i.e. how to design spectrum access strategies and how to develop mathematical models for evaluating the performance of these strategies, in order to improve the QoS of future networks. We focus on developing analytical models based on CTMCs that are applicable to the proposed strategies and can capture the interdependence and dynamic relationships between the underlying cellular system components. Queueing theory is used to analyze the behavior of such complex systems and to make intelligent decisions in their management. Accordingly, the conclusions of the research presented in this thesis can be summarised as follows:

1. To investigate the effect of signal quality while evaluating the cellular network performance, call admission control strategies are designed in Chapter 3. The performed analysis reveals that the suggestion to re-handoff the poor quality calls in the proposed strategy, instead of immediate dropping, leads to significantly improved system performance. The carried out analysis suggests optimal new call acceptance probability and shows that under the joint effect of FGC policy and queueing scheme, the proposed strategies achieve a better trade-off of handoff dropping and new call blocking probability while maximizing resource utilization. In addition, the determination of an upper bound on queue size could guarantee a balance between throughput and average delay of services.

2. The performance of CRNs under an imperfect sensing environment is evaluated in Chapter 4. A major feature of the proposed strategy is that it not only takes into account the effects of sensing errors by incoming SUs but also consider the misdetection and false alarm probabilities by already transmitting SUs. The effect of FARs is also captured on the operation of CRNs. The FARs can severely degrade the performance of SUs and reduce the overall spectrum utilization. However, the integration of queues and retrial phenomenon allows SUs that would otherwise be blocked or forcibly terminated to be buffered and possibly served later, thereby results in enhanced system performance.

3. The reliability and the availability of CRNs are analyzed from dependability theory's perspective in Chapters 5 and 6. Based on the analysis performed in Chapter 5, a higher retainability level of ongoing transmission sessions of both PUs and SUs, and improved network unserviceable probability can be achieved through channel reservation. Moreover, the retrial phenomenon and impatient behavior (balking and reneging) significantly influences the CRN performance by enhancing the performance of SUs. Furthermore, it is revealed from the results derived in Chapter 6 that the multi-level channel reservation might not necessarily provide improved performance. Its success highly depends on the network load and

time elapsed. Both channel failure rates and repair rates have a great impact on the network performance thus, can be tuned to achieve better trade-off in terms of availability and reliability to the end users.

4. The performance of cellular mobile networks is evaluated using a $MAP/PH/1$ queueing model under working breakdowns and working vacations in Chapter 7. The proposed model is shown as a generalization to a number of queueing models in the literature. In addition, the decomposition results for mean number in the system under special cases are proved and are shown to be in agreement with the previously published ones. Certain insights into the model are presented through some numerical illustrative examples, which include variation in arrival process as well as service process and importance of account of correlation. In the context of distribution of the inter-arrival times as well as the service times, our analysis validates the fact that variance in addition to the mean is important in determining the performance measures.

In conclusion, the strategies and the analytical models discussed in this thesis collectively provide a systematic approach to the analysis of availability and reliability for channel access in cellular mobile networks. The proposed models can be used to develop practical and more accurate cellular network performance evaluation models.

8.2 Specific Contributions

The thesis contributes towards different stochastic models of cellular networks including CRNs. Moreover, the work presented in this thesis provides new insight into the operation of cellular networks and gives a comprehensive solution to the question on how to improve the network performance by adopting various proposed techniques. Throughout the study, the main findings as specific contributions are highlighted as follows:

1. Several transient or steady-state availability and reliability performance measures in mathematical expressions are provided for the straight forward computation and analysis of the performance of cellular system.

2. The distribution of the effective service time of a customer in the context of server breakdowns, repairs, and backup model is computed by employing the matrix-analytic method.

3. Another remarkable contribution is that a joint design of continuous spectrum sensing and channel access mechanism is proposed. It is observed that the imperfect sensing parameters, notably FARs have a major impact on the CRN performance by degrading both heterogeneous SUs' and PUs' performance, thus the effect of sensing errors should not be ignored while modeling the network. The designed DSA strategies and queueing models would help the network operators to make a better decision for developing systems with sufficient and diverse QoS.

4. To enhance the service retainability level of CRN users in the presence of random channel failures, channel reservation schemes are developed and in-depth study of the reliability aspect is done from the dependability theory's perspective, which could help to provide reliable services in the next generation wireless networks. It has also been observed that it is pertinent to study such networks in the time domain.

5. The present study also reveals that if the inter-arrival times of packets are not independent, impelling them to be independent may underestimate/overestimate the performance measures and this may result in an erroneous network dimensioning. Thus, due to the bursty nature of Internet traffic, there is a requirement to capture correlation of packets in future networks.

8.3 Future Work

The research conducted in this thesis has expanded the horizons for a few potential topics. In brief, the following directions are foreseen.

1. The arrival pattern of users is considered as single arrivals in this thesis. The analysis can be further extended for users with batch arrivals to deal with the bulk arrival

of packets in networks.

2. Following the approach in Chapter 3, one can incorporate the mobility pattern of an individual user by using the simulation of arrivals in order to more accurately see the effect of signal quality.

3. The model studied in Chapter 4 considering homogeneous channel environment can be extended to investigate how the performance of a CRN is influenced by traffic load under heterogeneous channel conditions. Specifically, it can be done by considering two types of channels which have different bandwidth and transmission rates.

4. The works that appeared in Chapters 5 and 6 can be extended for dynamic channel reservation schemes rather than static schemes. That is, the impact of channel reservation can be investigated considering a dynamically adjusted set of channels and further optimal number of reserved channels can be obtained.

5. In the developed framework for performance evaluation of channel reservation schemes, the analysis is performed only in the time domain. The joint time and space domain analysis appears as another important research task.

6. The retrial times (Chapter 5), failure times, repair times (Chapters 5-7) and vacation times (Chapter 7) are considered to be exponentially distributed in the analysis performed in this thesis. The similar analysis can be carried out for more generalized distributions such as assuming them to be of phase type.

7. The working-vacation-breakdown-repair queueing model studied in Chapter 7 can be generalized to multi-server case, but the dimension of the problem will increase significantly.

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